ORDÓÑEZ

Lightning Protection for Electric Railways

Railway Electrical Engineering

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LIGHTNING PROTECTION
FOR
ELECTRIC RAILWAYS

BY

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P R E F A C E

The subject of lightning protection is one which has for many centuries been investigated, but which until recent years has remained inexplicable. The extremely variable character of the lightning discharge renders its close study exceedingly difficult. It is furthermore almost impossible to produce laboratory conditions which exactly simulate the effects of natural discharges. In spite of these facts, many investigators have studied the problem, and the number is being constantly augmented.

At the present time, the methods used for protection against lightning all have one general principle of operation. Instead of trying to avoid the discharge, it is guided through predetermined paths and suppressed, thus leaving unhurt the objects to be protected. So far, perfection has not been attained, but every effort has been made to approach ideal conditions, while at the same time keeping within justifiable limits of expenditure.

If the cost of damage due to lightning is taken into consideration, it will be found that the subject deserves the most serious consideration, not so much by the manufacturers as by the users of the protective devices. A large concern will frequently object to employ a lightning arrester

expert to be constantly on the lookout for defects and to study the behavior of protective apparatus in the system, but at the same time may be forced to pay large repair bills for damaged apparatus, which might have been reduced very considerably by keeping the protection in good working condition. On the other hand, the reports from many model installations on the behavior of up-to-date protective apparatus have started a decided movement for adequate lightning protection.

The present investigation was taken up at the suggestion of Mr. L. P. Crecelius, President of the American Electric Railway Engineering Association for the year 1914-15. It was brought forward as one of the most important questions confronting the electric railway industry to-day. No attempt has been made to develop any new data, but rather to compile and discuss both the experimental and the theoretical information that has been made public, especially in America, although some European articles have been carefully studied.

It is the hope of the writer that the information contained herein will aid in making progress toward better forms of lightning protection and better use of the existing types of equipment.

The writer wishes to acknowledge the assistance of every manufacturer of lightning protective devices in the United States, who all furnished data and descriptions which were of value in the preparation of this thesis. Other sources of information were published articles and reports,

which are referred to in the foot notes and in the bibliography of Chapter XI.

CHAPTER I

ATMOSPHERIC ELECTRICITY

Before taking up in detail the subject of methods of protection from lightning discharges, it is desirable to investigate the apparent causes of electrical disturbances in the atmosphere.

Among the early experimenters, Benjamin Franklin was the one who contributed the most to the subject. He began his researches in 1747 and shortly after was able to state the results. He found first, that the upper strata of the earth's atmosphere are electrically charged and second, that under normal conditions there is a gradual increase in potential with the altitude. These two statements pave the way for extensive investigations. The first problem is to determine the nature of this electrification of the atmosphere as well as its cause and second, to determine the character of the ultimate effect of this electrification, namely, the electric discharge.

By observation of the coincidence of certain of our atmospheric phenomena with the visible changes in the structure of the sun's surface, we feel justified in assuming that our central star is a highly charged body.

As a matter of fact, sciencists have shown that ionic rays, such as α, β and γ rays emanate with the light from all luminous sidereal bodies. Our globe therefore forms part of an

electrical system and is, like any other body, subject to the laws of nature.

For simplicity in our discussion, only the effects of the sun will be considered.

The β rays, which consist of negative ions, are easily deflected by the earth's magnetic field while traversing our atmosphere. They are, therefore, forced to follow more or less spiralled paths, terminating at the earth's surface in the arctic and antarctic regions. Under favorable circumstances, these ionic streams cause the phenomena called auroras.

The α rays, being composed of positive ions, are not appreciably deflected by the earth's magnetic field and follow very nearly the paths of the light rays. The α rays very seldom reach the earth, for their charges are totally absorbed by the matter in the middle and lower strata of our atmosphere.

The γ rays, which like the α rays are positive, are the most penetrating. They combine their charges with those of the matter in the atmosphere and reach even the surface of the earth.

Consequently, the upper portions of our atmosphere are electrified by the α, β and γ rays; the middle strata by the α and γ rays; and those near the earth's surface by the γ rays only. Hence the formation of the potential gradient of our atmosphere.

There are many factors controlling the nature of this gradient, but it has been found that the most influential

ones are: (1) The presence of road and desert dust raised by the wind; (2) The presence of dust raised by certain manufacturing operations; and (3) The presence of steam and water vapor. #

1.-- Road and desert dust generally diminish the potential gradient and occasionally even reverse it, as often observed in Africa.

2.-- The manufacture of cement gives rise to dust of different characteristics from road dust. Cement dust increases the positive charge of the atmosphere. Investigators have shown that cement factories are subjected to very high potentials. Potential gradients as high as 290 volts per foot have been recorded at a distance of about 300 feet from a cement factory building, while in open ground the gradient was about 35 volts per foot.

3.-- The presence of moisture in the atmosphere seems to exert the greatest influence on the potential gradient. This latter varies almost directly with the amount of moisture in the air.

There are other factors of minor importance such as rain, hail and snow, whose effect is to increase the potential gradient. This increase is perhaps due to the minute charges which the falling particles carry down in their descent.

Now let us assume this gradient under normal conditions and investigate the electrophysical phenomena that

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#--"Some sources of disturbances of the normal atmospheric potential gradient." By W. A. D. Rudge. Elec'n. Lond. 7-30-1915.

occur during the formation of rain, hail and snow.

Our atmosphere is continually receiving moisture, due to the evaporation of water from the earth's surface.

With the addition of water vapor to air at any given pressure and temperature, a point will be reached at which the air will not hold any more moisture and beyond which, condensation will take place. This is called the saturation point and occurs where the vapor pressure reaches the pressure of the mixture. Such a point may also be reached by lowering the pressure of moist air. If this pressure is still further decreased, condensation takes place until equilibrium between vapor pressure and that of the mixture is reestablished.

The moisture in our atmosphere exists in two different forms: water vapor and water in suspension. The latter is visible but the former is not. Clouds are formed by the condensation of water vapor into small water globules which remain in suspension in the air.

When a cloud is subjected to a considerable decrease in pressure, further condensation will occur, which increases the weight of the globules and causes them to descend.

The clouds in our atmosphere are subject to changes in pressure, due to air currents and other causes. Under favorable circumstances changes in pressure may cause rain or other forms of precipitation.

Let us consider a portion of a cloud which is being subjected to a decrease in pressure sufficient to cause condensation. Assuming, for simplicity, that the little drops in

suspension are of uniform size, we may infer that if their potential is that of the region in which they lie, their electrostatic charges may differ from each other only by very small amounts, and consequently we may consider them equal.

When condensation begins in an upper, highly electrified stratum, the little drops of suspended moisture descend, encountering drops and combining their masses as well as their electrostatic charges. The latter add directly as the masses but the electrostatic capacity does not increase so rapidly, since it is a function of the linear dimensions of the drops. Thus, a drop composed of eight of the original drops will have eight times the original charge, but only twice the original capacity, and consequently, four times the potential.

Therefore, every descending drop conveys an electrical charge from the clouds in the upper strata to those further down.

The lower clouds are insulated conductors and accumulate these charges until their potentials with respect to the surrounding bodies are so high that discharges occur.

The discharge of a cloud, like that of a condenser, is a function of its capacity and of the impressed potential. Since neither one of these can be determined offhand for a given cloud or a system of clouds, it follows that it is impossible to estimate, by any known method, the magnitude of atmospheric discharges.

In the following classification, it is intended to give a comparison of the different types of discharges as they

would occur under a typical set of conditions.

Let us imagine a system of clouds A, B, C, D, etc. such that cloud A is the nearest to the earth and the others are at reasonable distances from A but somewhat higher up; and assume that rain is being formed in the upper strata and that the whole system is being charged. Under these conditions, different types of discharges may occur, as follows:

1.-- The simplest form of discharge is that due to the gradual accumulation of charge in cloud A from the rain drops falling through it; in which case, the cloud potential will simply increase until it reaches the disruptive value. Evidently, there cannot be any milder discharge from the cloud under the given circumstances. Thus, we shall use this discharge as a reference.

2.-- Suppose cloud A has not yet attained the disruptive potential, and that cloud C, for instance, receives a discharge from a cloud still higher up. The sudden charge of C will induce a corresponding charge in A. The potential of the latter may thus surpass its disruptive potential and the discharge will be correspondingly more severe.

3.-- Assume the conditions of the second case, except that cloud C not only induces a charge but actually discharges over A, thus suddenly raising its potential to many times the disruptive value. In this case, the most terrific discharge occurs.

4.-- After the discharge occurs as in the second case, the cloud A, as a whole, is left at a much lower potential

than it previously had, consequently a discharge from C is the most probable. In this case cloud A may again be raised to a potential exceeding the disruptive value and a second discharge will take place.

5.-- After the discharge occurs, as in case three, cloud A, being left at a relatively low potential with respect to the earth, will receive discharges from the neighboring clouds and repeat the discharging process a number of times. This is perhaps the cause of the so called multiple discharges. The succession of these is at times so rapid that as many as 48 discharges in 0.625 seconds have been recorded by photographic apparatus.

6.-- Finally, any possible combination of the above cases.

So far we have considered the lightning discharge simply with respect to the earth's surface. This consideration applies readily to all objects exposed to the atmosphere and electrically connected to the earth, such as buildings, structures, etc.

With the development of electricity it became necessary to string electrical conductors over the earth's surface and insulated from it, such as telegraph, telephone and power transmission lines. The introduction of this new factor into the field of activity of atmospheric electrical phenomena has added many complications to the problem of lightning protection.

C H A P T E R II

LIGHTNING

The term lightning, for many centuries was taken to comprise:[1] "The flash of light produced by the discharge of atmospheric electricity from one cloud to another or from one cloud to the earth; hence, the discharge itself", or simply[2]: "The visible flash that accompanies an electric discharge in the sky", has now been modified in order to satisfy modern requirements. Lightning, therefore, denotes: "all phenomena of abnormal voltage and abnormal frequency".

With this definition as a basis, we shall classify lightning phenomena in electric circuits as follows:

1.-- External lightning: disturbances due to atmospheric electricity;

2.-- Internal lightning: disturbances due to defects of circuits or in their operation; and,

3.-- Surges: disturbances in the generated power caused by either or both of the previously mentioned disturbances. The magnitude of these surges depends on the power of the generating system wherein they occur.

A somewhat different classification, however, based on the nature of these phenomena will greatly simplify our discussion:

1.- Webster's International Dictionary.

2.- Encyclopaedia Britannica, 11th. Edition.

A.-- Gradual electric charge;

B.-- Impulses or traveling waves;

C.-- Standing waves and oscillations; and,

D.-- Surges.

ELECTRIC CHARGE

The accumulation of electric charge on insulated electric systems is oftentimes the cause of abnormal potentials. This gradual accumulation of charge may be due to:

1.-- The collection of static charge from the electrified particles of rain, hail, snow or fog carried by the wind across the line.

2.-- The variation in altitude and atmospheric potential of different portions of the line.

3.-- Electrostatic induction from passing clouds.

4.-- Accidental electrostatic charges, as those originated by belt friction and carried through the line by electrostatic induction.

5.-- Unsymmetrical or abnormal conditions in the generating circuit, due for instance to a grounded phase.

When a line has attained the disruptive potential at its weakest point, it will discharge through that point, and consequently, the electrical equilibrium being disturbed, oscillations will result and perhaps develop into destructive surges.

IMPULSES OR TRAVELING WAVES

When a conductor is charged and the electrical equilibrium has been restored (that is: there is no current flowing), the amount of energy stored is proportional to the electrostatic capacity C and to the square of the voltage e, to which the conductor is raised with respect to the earth. That is to say: the electrostatic energy is equal to $\frac{1}{2} e^2 C$. However, if this charge finds a path of inductance L and the current i flows through it, then the electrostatic energy is transformed into electromagnetic energy $= \frac{1}{2} i^2 L$, and if the end of the conductor is perfectly insulated, the energy will again be transformed into electrostatic and the process continued until the entire energy is transformed into heat by the unavoidable presence of resistance in the electrical conductors, the loss being $i^2 R$ in watts, where R is in ohms and i in amperes.

The above described phenomenon is called an impulse or traveling wave. The transfer of energy in the system is performed at a definite frequency f, where

$$f = \frac{1}{4\pi\sqrt{L\ C}}$$

Assuming, for simplicity, no losses we have then the general energy equation,

$$\frac{e^2\ C}{2} - \frac{i^2\ L}{2} = 0$$

where e and i are corresponding instantaneous values. Therefore, e attains a maximum value e_o for i equal to zero and vice-versa. The process is exactly analogous to the transfer of energy in a pendulum in changing from kinetic to potential and vice-versa. Friction in this case corresponds to the electrical losses.

From the principle of conservation of energy we have:

$$\frac{e_o^2 C}{2} = \frac{i_o^2 L}{2}$$

or

$$e_o = i_o \sqrt{\frac{L}{C}}$$

Thus, the term $\sqrt{\frac{L}{C}}$ acts somewhat as the impedance and for this reason it is called the "surge impedance" of the line. When the frequency of the wave coincides with the natural frequency of the line, the wave is called a "free oscillation", and when an oscillation is impressed upon the circuit, having a frequency different from the natural period of the line, it is called a "forced oscillation".

Traveling waves are the result of:

1.-- Lightning strokes entering the line. These strokes may be direct or secondary.

2.-- Electrostatic induction by passing clouds.

3.-- Discharges of slowly accumulated potential resulting in a series of successive impulses.

4.-- A spark discharge from a line to another line or to ground.

5.-- An arcing ground on one phase of an insulated system or in general, the existance of a self-repeating arc in a system.

6.-- Sudden changes of load; connection and disconnection of apparatus, lines, etc., also result in the production of traveling waves.

Long transmission lines are particularly adapted to show the most essential characteristics of traveling waves.

Transmission lines, like any other electrical conductor of considerable length, require charging currents in proportion to their capacities, but the inductance of the lines makes the flow of this current relatively sluggish.

Let us consider the effect of suddenly connecting a long transmission line to a source of power at constant voltage. A flat wave of current and voltage will travel along the line. The shape and magnitude of this wave will, however, be modified by the resistance of the line. But for simplicity in our discussion let us assume that the effect of resistance can be neglected.

The following are two of the fundamental facts concerning electrical waves:

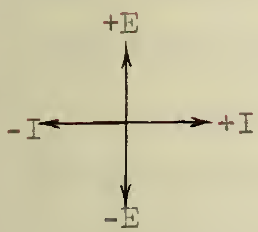
1.-- Electrical waves do not differ in behavior from mechanical waves and their laws are similar.

2.-- The current wave is a direct result of the potential wave.

Let Fig. 2a represent a wire which has just been connected to the positive terminal of a source of electrical

energy. Fig. 1 gives the nomenclature of voltages and currents represented in Fig. 2.

The voltage wave (Fig. 2a) will travel towards the open end of the line causing a simultaneous current wave.



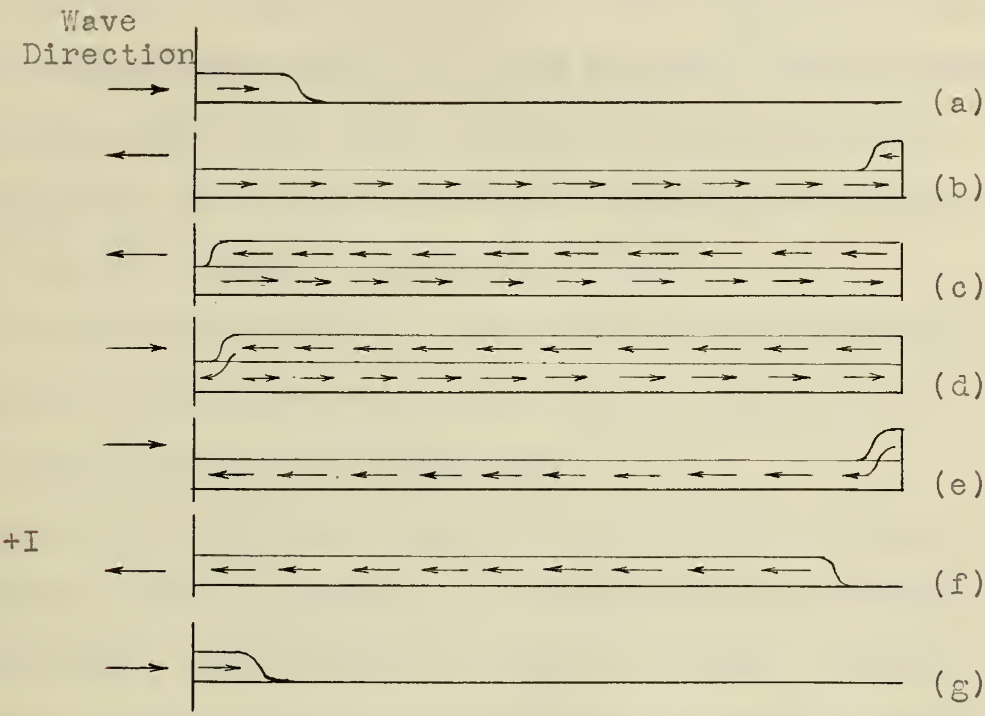


Fig. 1.—Current and Voltage Nomenclature.

Fig. 2.— Flat Wave of Current and Voltage on a Long Transmission Line.

When the voltage wave reaches the end of the line, it will either jump across to the other line, if the gap is small, or it will double its potential at the end and start a wave traveling in the opposite direction. This wave will be simultaneously followed by a current wave also in the opposite direction, Fig. 2b. After this second wave has passed, the voltage of the line will be twice the normal but the current will be neutralized. When this voltage wave reaches the

source, Fig. 2c, it will find through it an easy path to the other wire; therefore the current in the first wire will continue towards the source, Fig. 2d, discharging the line, so to speak, of the excess voltage, Fig. 2e; this discharge will continue until the current will find its path checked or there is no more voltage back of it. So, the wave will start towards the source (Fig. 2f) until the line is free from electrical charge. The source will again succeed in sending a new wave, Fig. 2g, which will simply repeat the process.

In practice, however, as the waves go back and forth, they diminish in magnitude on account of the losses and the line will soon attain normal potential.

If we consider a wave caused by a momentary closing of the switch, we will approach the conditions of an impulse or traveling wave. Thus we may say that an impulse doubles its potential at the end of an opencircuited line and travels back and forth until all of its energy is transformed into heat. If the line is open circuited at the far end and connected to the source, a potential wave, in reaching the source, will be reflected with opposite sign, which will again reverse at the next reflection. When two or more traveling waves happen to meet at any place on the line, their voltages and currents will add algebraicly, resulting in very high local strains on the line insulation.

STANDING WAVES

When an alternating voltage is impressed upon a long transmission line, the result is the combination of effects of a train of sudden impulses. The velocity of the direct and the reflected waves being exactly the same and their magnitudes very nearly the same, their combination results in a series of standing waves. The maximum potential of these waves will be nearly double that of the original waves.

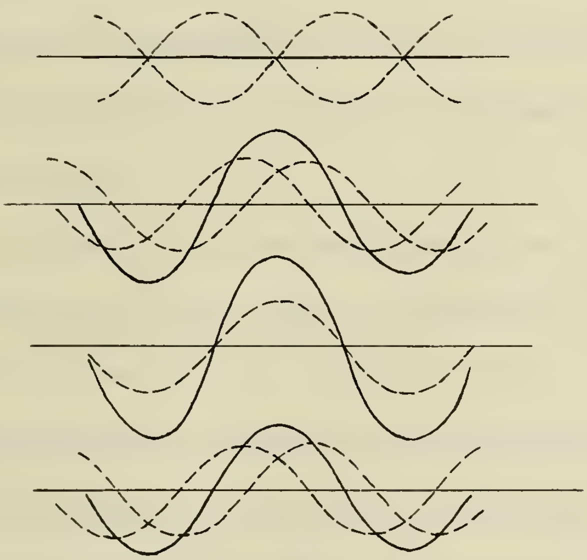


Fig. 3.– Formation of Standing Waves.

Fig.3 illustrates different stages in the formation of standing waves, caused by the combination of two trains of waves of about the same magnitude but traveling in opposite directions.

Occasionally conditions are such that the reflected waves reach the source just in time to reinforce the outgoing

waves. If the waves leaving the source thus increase in magnitude, their reflections will be correspondingly increased. Consequently the line will be subjected to very abnormal potentials.

The reflected waves may reach the source just in time to neutralize the out-going waves. In this case, periodical trains of waves will be sent to the line and periodical standing waves will result.

OSCILLATIONS AND SURGES

The transient phenomenon which accompanies the restoration of equilibrium in an electrical system is called an electrical oscillation.

An oscillation on a transmission line is a complex wave containing a fundamental and higher harmonics. Disturbances may and usually do produce oscillations which contain very high frequency harmonics; only in this case their effects are purely local. The effects may become universal when the oscillations include the fundamental and the lower harmonics, in which case the oscillations are called "surges".

Impulses are oftentimes the cause of oscillations where the power which oscillates is the generated power of the circuit. Hence, the possible destructiveness of this type of oscillation is limited only by the available power of the system and does not directly depend on the severity of the disturbance from which the oscillation resulted.

SOME TYPICAL FORMS OF OSCILLATIONS

1.-- Spark discharges to and from the line, as over some lightning arresters. The breaking up of traveling waves by the protective apparatus at the stations generally results in the formation of oscillations of millions of cycles per second.

2.-- Arcing grounds and similar discharges to ground from a line of any insulated system; the reflection of traveling waves; etc.

3.-- Charging and discharging a line; or connecting a "dead" transformer into the circuit; etc.

4.-- In general, changes in circuit conditions, as sudden changes of load; connecting or disconnecting a transmission line; the sudden opening of a short circuit; etc. are the causes of oscillations in which the fundamental frequency predominates.

5.-- Certain transformer connections in polyphase systems may produce low frequency surges consisting primarily of the fundamental wave. This occurs when, in the case of an accident, an unequal distribution of load or other causes, the open circuit inductance of a transformer coil is in series with the line capacity in the circuit of a "live" transformer. In such cases the surges are produced by conditions of resonance.

Standing waves or oscillations in electric circuits have an extremely variable frequency. The lower limit of

this frequency is that of the fundamental surge which, in very long transmission lines approaches the commercial alternating current frequency. In these cases, the generating system participates greatly in the oscillation. The upper limit of these frequencies is that of the discharge between the cylinders of multigap lightning arresters, which may reach several hundred million cycles per second.

The physical effect of oscillations depends, to a certain extent on the frequency and is therefore subjected to the most extreme variation. In very high frequency oscillations the power is quite small; the electrostatic effects most predominant are: luminous glow, brush discharge, streamers and sparks. The damage, on account of the small power involved, is correspondingly insignificant and the effect is local, for the obstruction offered by the inductance of the line becomes most effective at these high frequencies. On the other hand, the extreme low frequency surges show hardly any luminous displays. The effect of inductance is almost negligible, so that they spread their destructiveness all over the system, using for the purpose the power of the system itself.

Oscillations, therefore, are frequently subdivided into: high frequency oscillations, in which the lower harmonics are absent, and low frequency oscillations in which the fundamental predominates. The name surge is frequently applied to denote the latter. Oscillations of intermediate frequency, however, have considerable power and inductance offers them but little obstruction; they have luminous displays as strea-

mers and brush discharges. Oscillations of this intermediate class are occasionally produced by arcing grounds, spark discharges through defective joints, etc.

So far, we have discussed the four types of lightning disturbances as they occur singly, but in practice they generally occur in groups of several in succession, the one preceding causing the next in a great number of combinations. A few examples will make this point clearer.

A static charge raises the potential of a line until a break to the ground occurs, the discharge producing an impulse or traveling wave. When this wave reaches the station it breaks through the arresters producing a high frequency oscillation. A high frequency oscillation, puncturing the insulation, causes a short circuit which in rupturing causes a low frequency surge.

The discharging of a static charge over lightning arresters with sufficient damping generally causes a high frequency oscillation.

When a short circuit occurs by the discharging of an accumulated static charge in a line, it will cause a low frequency surge.

Low frequency surges may also be produced by the breaking of the dynamic circuit which tends to follow lightning arrester discharges.

The traveling wave produced by connecting a cable to a bus bar may cause a discharge from conductor to cable armor at some defective joint. The spark may develop into an oscil-

lating arc, in which case traveling waves are sent out along the cable. When these waves enter the station they may produce high frequency oscillations; and systems of such oscillations may follow each other with great rapidity corresponding to that of the impulses caused by the oscillating arc. This phenomenon may produce a continuous 'static' in the station which ultimately results in a short circuit somewhere, causing consequently a low frequency surge.

We could continue giving typical instances of the occurrence of these phenomena, but let it suffice to say that the number of combinations is unlimited.

TYPICAL CHARACTERISTICS OF ELECTRIC WAVES

In electric circuits, where the inductance and capacity are evenly distributed, as in a transmission line, any change of voltage or disturbance at any point causes an electric wave to travel along the line, raising its potential at the various points as follows:

1.-- A wave passing through a wire of uniform cross-section will not suffer any alteration except the diminution of amplitude due to the losses and will always travel at a definite rate. If the end of the wire is open, the wave will be reflected as already explained. If however, the end is short circuited or connected to a large condenser so that this point is maintained at zero potential, the voltage wave will be reflected with opposite sign. This change both in

direction and in sign will maintain the current in the original direction.

2.-- The open circuit conditions have already been explained in connection with traveling waves.

3.--Two or more waves passing one another add their algebraic values of voltage and current and each passes without affecting the velocity, intensity or form of the other.

4.-- When a wave on a line of large capacity passes into another line of smaller capacity, a partial reflection will occur at the junction. The reflected part of the original wave seems to be directly proportional to the difference in the percents of the capacities of the two lines. The unreflected part of the wave will travel at a new rate in the second line, this rate being a function of the line characteristics. The potential of the wave in the second line will be that attained at the junction where the partial reflection occurred. The potential of the second wave may therefore be nearly double that of the original; and if a line of much smaller capacity is connected at the end of the second line the phenomenon will be repeated, thus causing very abnormal voltages. The losses in the different lines will, however, greatly diminish these effects.

5.-- When a wave meets a division of the line into two or more branches or a line of larger capacity, the wave will continue in the same direction but correspondingly diminished in magnitude. In this case, the reflected wave in the first line will be reversed in sign.

6.-- When a system of considerable ramification is connected to a source of power, there may be conditions when the direct waves combine with agglomerations of reflected waves resulting in very high strains on the line insulation where peaks happen to occur.

7.-- When a wave encounters a choke coil inserted in the line or at the end of it, the wave suffers a reflection similar to that of the open circuit. If the coil does not possess inductance enough to detain the wave, the potential beyond the coil will be consequently increased. In such a case additional choke coils should be installed. Choke coils alone cannot effectively protect a station against in-coming disturbances, but they should act in conjuction with lightning arresters.

8.-- If the cause of static waves be periodic so that a succession of waves passes into the line, and the constants of the line be such that the reflected waves arrive at the source in time to reinforce the out going waves, resonance may occur, resulting in very abnormal voltages on the line.

9.-- When a traveling wave reaches a coil such as the high tension winding of a transformer, its speed in going around the coils is greatly diminished on account of their inductance and capacity. Hence, when the crest of the wave has reached the beginning of the coil, the front of the wave may have penetrated only a short way. Therefore, the outer portion of the coil is subjected to the full potential of the wave, while the rest of the coil is at relatively low poten-

tial. This results in punctures of insulation and in the creation of consequent phenomena as already explained.

10.-- The existence of an arc of considerable length in a circuit causes a great deformation in the wave form of the current. The effect is equivalent to the superposition of one or more harmonics of current on the fundamental. Such a superposition may, in some cases, produce a rise of potential in the line.

CORONA

In our previous discussion we had occasion to refer to electric discharges. We shall consider now the nature of these discharges as they take place through the air under normal conditions.

When the electric flux density in the air exceeds a certain value, a pale violet light appears near the surface of the conductors. This silent discharge is called electrostatic corona.

The formation of this phenomenon causes the ionization of the air; and at still higher voltages, streamers of electrons are sent off from the protuberances on the surface of the conductor, constituting the so called "brush discharge". If the voltage is further increased, spark discharges will occur following the path of most intense ionization. These three stages of development must precede chronologically all discharges in the air.

The subject of electrostatic corona is still under investigation. It will be very briefly discussed in this paper.

The electric strength of air varies almost directly with the pressure and inversely with the temperature, i.e., it is a direct function of the air density. Therefore, at high altitudes, brush discharge starts and break-down takes place at lower voltages than at sea level.

Therefore:

$$\frac{e_1}{e_2} = \frac{d_1}{d_2}$$

where e equals the sparking voltage and d the air density; the subscripts 1 and 2 correspond to particular conditions.

The density is a function of the barometric pressure and the absolute temperature,

$$d = 3.92 \frac{b}{T}$$

Where b is the barometric pressure in centimeters of mercury and T the absolute temperature in degrees centigrade.

Summarizing we have that,

$$\frac{e_2}{e_1} = \frac{d_2}{d_1} = \frac{T_1\ b_2}{T_2\ b_1}$$

For constant temperature it reduces to,

$$e_2 = e_1 \frac{b_2}{b_1} = \delta e_1$$

where δ is the relative density of the air when the barometric pressure at sea level is taken as a basis.

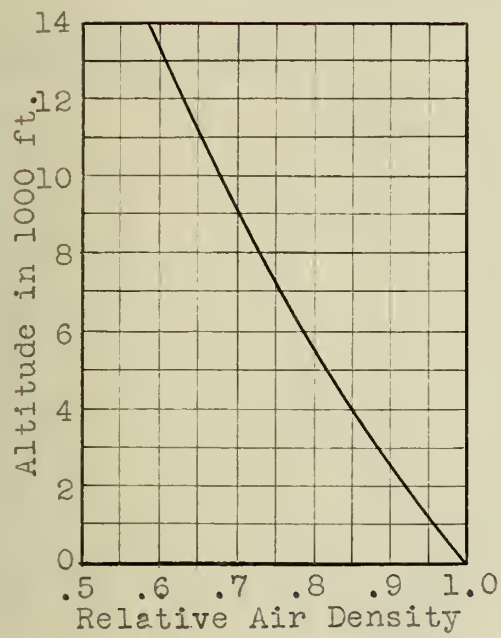


Fig. 4.

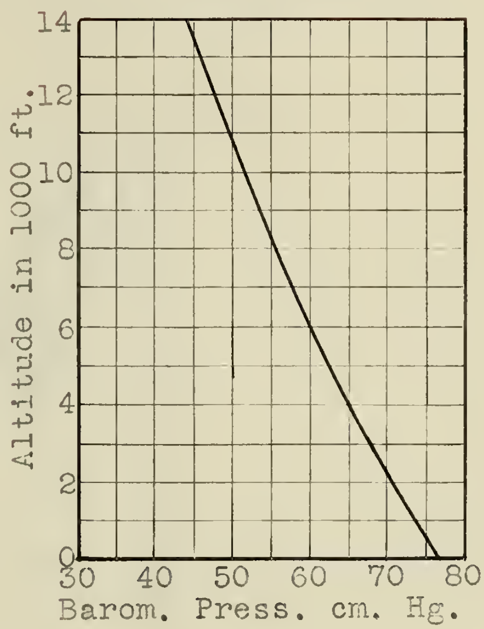


Fig. 5.

Fig. 4 shows the relation between the altitude and the relative density factor δ.

The relation between the altitude and the normal barometric pressure is shown in Fig. 5.

The disruptive critical voltage e_o is that voltage at which the disruptive potential gradient of the air is reached at the surface of the conductor. Hence, it is:

1.-- Proportional to the conductor's radius r and to the natural logarithm of the ratio $\frac{D}{r}$, where D equals the distance between centers of conductors, expressed in the

same units as r.

2.-- Decreased very slightly with the increase of frequency.

3.-- Proportional to the air density.

4.-- Independent of the material of conductor.

5.-- Dependent somewhat on the conditions of the conductor surface.

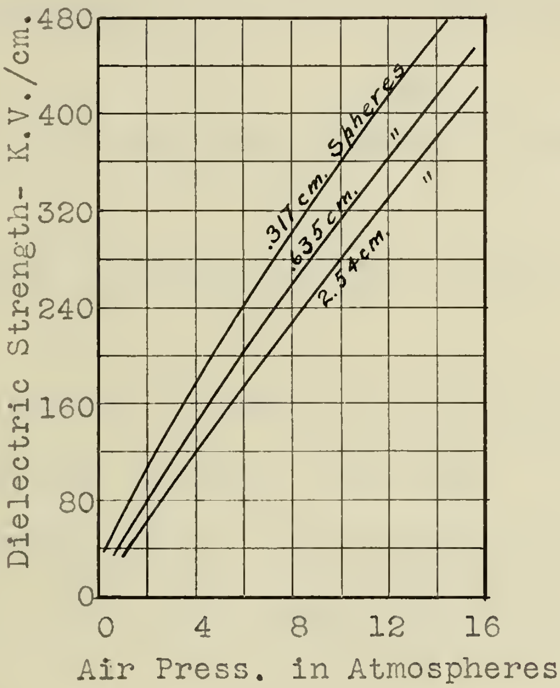


Fig. 6.-Sparking Potentials between Spheres.

6.-- Dependent on the stranding of the conductor.

7.-- The rate of change of the critical voltage with the pressure is greater for conductors of small diameter.

Fig. 6 illustrates this point at high pressures.

The energy lost in corona is:

1.-- Proportional to the square of the excess voltage above the disruptive critical voltage e_0.

2.-- Proportional to the frequency. (especially at

high frequencies.)

3.-- Proportional to the square root of the conductor radius.

4.-- Inversely proportional to the distance between the conductors.

The effects of various atmospheric conditions on the critical voltage are briefly as follows:

1.-- Humidity has no effect on the critical voltage or loss.

2.-- Smoke lowers the critical voltage and increases the loss.

3.-- Heavy wind has no effect on the critical voltage or the loss.

4.-- Sleet on the wires or falling sleet lowers the critical voltage and increases the loss.

5.-- Snow, rain and fog lower the critical voltage and increase the loss; snow being the most influential of the three.

Some sciencists have conceived the idea of using corona loss to dissipate excessive voltages on transmission lines and have designed apparatus for that purpose. We will speak of these later.

SKIN EFFECT

The mutual inductance of two or more conductors is an inverse function of the distance between their centers;

consequently, the mutual induction of the strands of wire near the center of a large cable must be greater than that of the strands at the surface.

This difference in inductance and consequently in reactance, naturally tends to intensify the current in the outer strands as the frequency of the impressed potential increases. This reasoning applies not only to stranded cables but also to solid conductors.

The phenomenon of intensifying the current on the surface of electrical conductors, is called "skin effect".

The reactance of the center strands, being a function of the frequency, will tremendously increase when conductors are subjected to frequencies such as those of lightning discharges. In such instances, the effective area of the conductor may be reduced to a fraction of one percent of the actual cross-sectional area. The radial thickness of the effective area being only a few ten-thousandths of an inch.

At first glance it would seem that conductors of magnetic materials cannot be used effectively for grounding purposes, but there are other factors entering into consideration. This question will be discussed in the following Chapter.

CHAPTER III

PRINCIPLES OF PROTECTIVE APPARATUS

A brief survey of the principles on which protective apparatus have been constructed, will aid greatly in understanding their characteristics and their adaptability to satisfy the requirements of modern practice.

The effectiveness of any protective circuit depends directly on the efficiencies of all and each one of its constituent parts. Consequently, the characteristics of each one of these parts should be carefully considered in order to choose the best possible combination under any particular circumstances.

PROPERTIES OF CONDUCTORS.

RESISTANCE

When a potential difference E is maintained constant between two points of a conductor and there are no electromotive forces within the conductor, the value of the current I is proportional to the potential difference

$$E = R I$$

where the coefficient of proportionality R is called the resistance of the conductor. This is the general statement for Ohm's law which presupposes isothermal conditions.

The resistance of metals generally increases with the temperature. There are conductors, however, whose resistance decreases as the temperature increases. This variation of resistance with the temperature is very slight in the case of metals, but other conductors, such as pulverized Brazil wood charcoal, reduce their resistances very markedly with relatively small rises in temperature.

The impressed voltage seems to have a great influence on the resistance of non-metallic conductors. Carborundum, for instance, has a very high resistance at potentials below a so-called critical voltage; but above this, its resistance is greatly reduced. Brazil wood charcoal possesses the same peculiarity in conjuction with its variation of resistance inversely with the temperature. Hence its adaptability for discharging surges of low periodicity.

INDUCTANCE

When a constant current is flowing in a circuit, there is a certain amount of energy stored in the magnetic field about the conductor. Should the current in such a circuit be made to vary by some external means, the magnetic field would react on the conductor, inducing in it an electromotive force in a direction tending to keep the current constant. Thus, if the current is made to change at a rate $\frac{di}{dt}$, the induced electromotive force E will be proportional to this rate of change, thus:

$$E = L \frac{di}{dt}$$

The proportionality factor L is called the coefficient of self induction or simply the inductance of the circuit. Inductance depends on the dimensions, shape and material of the electric circuit, but more directly on the dimensions of the magnetic circuit,

$$L == k \frac{A}{l}$$

where A is the area of the magnetic circuit and l its length. k is called the interlinkage factor and depends closely on the shape of the conductor.

The inductance of a circuit, depending on the dimentions and characteristics of its magnetic field, will naturally be affected by the presence of magnetic or high permeability materials anywhere in the magnetic field. Hence the objection to using iron or steel as conductor for alternating current at commercial frequencies.

When an alternating potential is impressed on a circuit containing inductance only, the effective current I will be proportional to the effective impressed voltage E,

$$E = I X_L$$

where the factor X_L is called the inductive reactance of the circuit. This latter, in turn, depends on the inductance L of the circuit,

[illegible]

$$X_L = 2\pi f L$$

where f is the frequency of the alternating potential in cycles per second.

If the circuit contains resistance R and inductive reactance X_L, the current I will also be proportional to the impressed voltage,

$$E = I\sqrt{R^2 + X_L^2} = I Z$$

where the factor Z is called the impedance of the circuit.

To summarize: the flow of alternating current through a circuit depends on the resistance and inductance, hence on the frequency, shape and material of the circuit. Irregular wave forms in the impressed voltage increase the reactance and impedance of circuits, on account of the introduction of harmonics of higher frequencies which cause the irregularities in the waves.

The effect of the permeability of magnetic materials is very marked at low frequencies, but gradually becomes less as the frequency increases; so that at very high frequencies, such as those of lightning discharges, the effect is practically nil.

This property of magnetic materials is of paramount importance in the design of protective devices and systems.

High frequencies also cause "skin effect"in conductors of considerable size, greatly reducing their effective area. This phenomenon was discussed in the previous chapter.

Since lightning discharges generally consist of very

high frequency oscillations their effects on conductors are summarized as follows: At very high frequencies,

1.-- The reactance and impedance of the circuit are correspondingly high.

2.-- The effective area of the conductor is reduced to a thin layer near its surface.

3.-- The effect of permeability of magnetic materials becomes practically nil.

Therefore, in order to have the greatest effective conductivity for high frequency currents, conductors should be:

1.-- Of high conductivity, regardless of magnetic properties.

2.-- Of such a shape and cross section as to have maximum periphery. Round solid conductors are absolutely the worst in this connection.

3.-- Kept as straight as possible throughout the circuit.

It has been found through years of experience that resistors connected to protective devices often improve the operation of the latter.

The desirable characteristics of resistors, as used for lightning protection purposes, are as follows:

1.-- Sufficient heat absorbing and dissipating capacity.

2.-- Surface of such a character that arcs will not flash over.

3.-- Must be easily replaceable.

4.-- Non-absorptive over section.

5.-- Uniform conductivity over section.

6.-- Non-inductive and straight.

7.-- Should have no coherer action.

8.-- Should have sufficient mechanical strength to stand red heat without failing.

9.-- Must not become incandescent under service conditions.

10.-- Should not deteriorate with use.

11.-- Should have high specific resistance.

12.-- Its resistance should not change with the use.

13.-- Must permit making good and permanent connections to the circuit.

These characteristics, however, do not entirely satisfy all the requirements of modern practice. There are a few special types of resistors to be used in series with spark gaps, whose characteristics approach more closely those of the ideal resistor.

There is a type of resistor on the market called "Skin Resistance" which consists of a terra-cotta pipe coated with platinum chlorid. This resistor has the peculiarity of offering a freer path to quick discharges than to slow ones. This type of resistor is, therefore, particularly well dadpted for use in series with any spark gap arrester.

The "Compression Chamber" arrester shown in Fig. 33 uses a novel type of resistor which consists simply of a treated carbon rod moulded with brass rings at frequent intervals, leaving a series of gaps on the surface of the rod.

When the potential drop across the resistance rod attains abnormally high values, the gaps between rings break and practically short-circuit the resistor.

The resistor used with the surge dischager, Fig. 74 and with the high frequency discharger, Fig. 75, also increase their conductivity when subjected to severe discharges. This increase in conductivity is due simply to the characteristics of the conductor. The pulverized charcoal used has a large negative temperature coefficient.

PROPERTIES OF DIELECTRICS.

CAPACITY

Capacity is a property of dielectric circuits and depends directly on the dimensions and material of the dielectric.

When a dielectric circuit, such as an open circuited line, is connected to a source of electric energy, the current flow I will be proportional to the time-rate of increase of the potential, namely:

$$I = C \frac{de}{dt}$$

where the factor C is the electrostatic capacity of the circuit. It depends on the dimensions of the dielectric circuit,

$$C = K \frac{A}{l}$$

where A is the area of the dielectric circuit, l its length and K is the dielectric flux constant, depending on the material of the dielectric.

The specific capacity of a dielectric is the ratio of its capacity to that of air, both referred to standard conditions of pressure and temperature. This ratio is a constant for all dielectric flux densities up to a certain critical value. If the potential is still further increased, the dielectric ruptures and its insulating properties are destroyed.

In practice, failures of dielectrics are generally caused by transient voltages. The behavior of dielectrics under such conditions is still under investigation.# However, several facts of practical interest have been established.

The rupture of gaseous, liquid and solid dielectrics requires an expenditure of energy; consequently the time element must enter into consideration.

The lapse of time between the application of the voltage and the rupture of a given dielectric is called its "time-lag". The latter is a function of the rate of application of potential. When the potential is applied at a very rapid rate, as by an impulse of steep wave front, spark-over does not occur when the continuously applied break-down is reached. The potential rises above this value and even continues to rise while the gap is discharging.

#-- "The effect of transientvoltages on dielectrics." by F. W. Peck Jr. -- Pro. A. I. E. E., Aug. 1915.

The time-lag depends on the rate of application of potential, the nature of the dielectric, the dielectric field, the shape and spacing of the electrodes, the initial ionization of the dielectric and other variables.

Dielectrics can be classified into three groups: gaseous, liquid and solid.

1.-- Gaseous dielectrics have a high self-repairing quality and the shortest dielectric time-lag. For air this latter can be expressed in microseconds.

2.-- Liquid dielectrics, such as oils, have also the self-repairing power but are decidedly more sluggish in recovering than gases. One second is sometimes required for transformer oil to fully recover from a heavy discharge. The dielectric time-lag of oils is very much longer than that of air or any other gas, and can be estimated in milliseconds.

3.-- Solid dielectrics have naturally no self-repairing qualities and are subject to "cumulative damage"; i.e., they deteriorate when placed under potential strains. Soft dielectrics, such as rubber, fibre, etc. are more susceptible of deterioration than porcelain or assembling cements.

The insulation of high voltage generators working at altitudes that allow the formation of slight corona, is subject to very rapid deterioration.

In designing insulators, the dimensions should be made such that the flash will go around the porcelain rather than through it.

Overheating of solid dielectrics is also very destruc-

tive and should be avoided whenever possible.

When an alternating potential is impressed on a circuit containing only capacity, the effective current is proportional to the effective impressed potential,

$$E = I\ X_C$$

where X_C is the capacity reactance, depending directly on the capacity of the circuit,

$$X_C = \frac{1}{2\pi f\ C}$$

Finally, when the circuit consists of resistance, inductance and capacity in series,

$$\begin{aligned} E &= I \sqrt{R^2 + (X_L - X_C)^2} \\ &= I\ Z \end{aligned}$$

where Z is the total impedance of the circuit.

In such a circuit, if the frequency of the impressed potential is gradually varied, a value will be found at which the inductive and capacity reactances are equal. Under such conditions the stored energy will freely oscillate between the capacity and the inductance, causing the phenomenon of resonance. If resonance takes place in a circuit, the stored energy will alternate from electrostatic at the condenser to elecrtomagnetic at the inductance, in such a way that the impulses of the impressed voltage will always come at a time to help and continually increase the oscillating energy. This energy must be dissipated either through the

resistance loss or by discharging over the points of weak insulation.

The magnitude and rate of increase of these oscillations naturally depend on the amount of inductance and capacity in the circuit. For this reason it is advisable to keep these latter as small as practicable in circuits intended for the discharge of oscillations of the frequency and potential occurring in atmospheric discharges.

NATURE OF ELECTRIC DISCHARGES

The electric spark has been the most useful factor in the design of protective apparatus and at the same time it has been a source of danger on account of its after effects. It is, therefore, of extreme practical importance to study its nature and characteristics.

As discussed in Chapter II, the formation of a conducting bridge between two electrodes, under electric strain, is due to the phenomenon called electrostatic corona. After this conducting bridge or ionized path is formed, if the voltage continues to rise, a spark will follow the path of greatest ionization. Assume, for example, two insulated spheres, A and B, gradually approaching each other and oppositely charged and that sphere B is at zero potential with respect to the earth. A distance will be reached at which the electrostatic energy stored in A $(= {}^{1}/_{2}\ C\ e^{2})$ will be suddenly transformed into the electromagnetic energy of the current flowing through the ionized path of the spark.

Some of the energy leaving A will be dissipated as heat by the arc and the rest will constitute the charge of sphere B. But the path, having been left highly ionized by the first spark, will allow a second discharge to follow in the opposite direction and the process will be repeated until the spheres are left at such a potential with respect to each other that no spark can be established in spite of the highly ionized path between them. This succession of discharges takes place in lapses of time estimated in microseconds or even fractions thereof.

If one of the spheres under consideration is connected to the end of an insulated conductor of considerable length, the variation of potential to which the sphere is subjected, will create a train of traveling waves in the line, which after reflection at the end of the line will constitute a series of standing waves and consequently, may strain and break the line insulation.

The characteristics of the spark gap, i. e., its nearly infinite resistance up to a certain critical value of voltage and its low resistance when this value is exceeded, (on account of the formation of the arc), makes it particularly adapted for discharging over potentials in systems of small capacity where the after effects cannot become harmful.

Certain metals, when reduced to a gaseous state, behave in a very peculiar way as regards the passage of electric current through them in the form of sparks or ionic streams.

Mercury vapor, for instance, when in an ionized state

allows the flow of current in one direction only; hence its adaptability in rectifying alternating current. Mercury is not the only metal possessing such characteristics; all monoatomic metals such as cadmium, mercury, zinc, etc. have this rectifying property to a more or less marked degree.

Extensive investigations were carried on by Mr. A. J. Wurts, the discoverer of this valuable property of monoatomic metals, about 1890, resulting in the development of the so-called non-arcing multigap which revolutionized the standard practice of protective apparatus at that time.

The principle of the non-arcing gap is briefly as follows: When a discharge occurs between two blunt non-arcing metal electrodes, about .03 of an inch apart, the heat of the arc causes liquefaction and vaporization or simply sublimation of a very thin coat of the metal, thus substituting for the air in the gap a monoatomic metal gas possessing rectifying properties. As soon as the first half wave has passed, the arc ceases and the gap then acts as an excellent dielectric for the reversed impulse that follows.

Several alloys have been found to possess the non-arcing quality to a higher degree than the pure metals. On this account they are always used in the manufacture of multigap arresters.

When an accumulated charge in a line in service is discharged through an ordinary spark gap, the ionized path of the spark is used by the dynamic current in the system to flow to ground causing short circuits and the consequent

damage. Many attempts have been made to avoid the formation of the arc, that is, the passage of the dynamic current immediately after the lightning discharge.

The fusibility of wires in series with the gap was first intended to solve the problem, but the difficulty and danger of replacing the fuses compelled the designer to apply other principles to extinguish the arc. Coils were then tried to operate systems of levers that would lengthen the arc to extinction. Later on, plungers, directly operated by the coils, were built to constitute the electrodes of the gap. The expansion of air due to the high temperatures of the arc also served as a means of separating the electrodes by placing the gap in suitable chambers fitted with more or less complicated mechanisms. The decrease in density of ionized air at high temperatures has been a factor of great usefulness for lightning protection. The horn gap arrester and all its modifications are based upon this principle. The action of the magnetic field on the electric spark is also used to drive the arc out of the gap and extinguish it.

The high resistivity and self-repairing property of a water column or stream has also been tried to free systems from over potentials.

Recent scientific researches have led to the discovery of peculiar properties of certain chemical solutions. When an electrolyte,made up of a certain solution of permanganate of potash, is put between two aluminum plates coated with a thin film of aluminum hydroxide, and an increasing potential

is slowly applied to the plates, a very small current will flow; but when the potential reaches the so-called "critical voltage" of the cell, the current flow will be several hundred times greater.

Two theories have been advanced to explain this behavior. First, that the electrolyte, being under an electric strain of such a nature, generates a counter electromotive force of a certain limited value, called the critical voltage, and consequently, if the impressed voltage exceeds the critical voltage, the superpotential or the difference between these two values, will send a current through the low resistance of the cell according to Ohm's law.

The second theory is that the hydroxide film on the aluminum plates is of such a nature that, when the potential reaches the critical value, the film becomes porous in proportion to the superpotential, thus allowing the low resistance electrolyte to come in contact with the aluminum plates thus forming a low resistance circuit.

The first of these theories seems to correspond a little more closely to the facts, especially when considering the action of the "liquid electrode" arrester recently developed on similar principles, and in which there is no film to act as a valve.

The corona losses at high potentials have recently been utilized as a means of dissipating the energy of slowly accumulated charges in transmission systems.

Perhaps one of the most important principles in the

protection of electric systems from atmospheric disturbances is the well known principle of Faraday's "cage": Any insulated body inclosed in a highly conducting and well grounded "cage", is almost absolutely free from external electrical disturbances of any character.

In practice, this principle has its greatest application on systems exposed to atmospheric disturbances; and although the conductors are seldom entirely surrounded by the protective "cage", a very satisfactory protection is obtained by stringing one or more heavy and well grounded conductors above the line wires.

C H A P T E R I V

GROUNDING METHODS.

GROUNDING CONDUCTORS

A very large portion of the failures in operation of protective apparatus is due to deficient grounding.

The efficiency of a complete protective system depends first, on the effectiveness of the ground conductor and connections and second, on the characteristics of the protective apparatus used.

The metals most generally used for grounding conductors are steel, iron, copper and zinc. A brief consideration of the adaptability of each one of these metals for grounding conductors and connections is of practical interest.

The electrical properties of all these metals were discussed in the previous chapter. In brief, magnetic materials lose their magnetic properties when subjected to alternating fields of high frequencies; and the effectiveness of all conductors is greatly reduced when discharging currents of abnormally high frequencies, on account of the formation of the "skin effect" phenomenon.

Liability to corrosion of the different metals must be considered in selecting the proper type of grounding devices and conductors for any given conditions.

Wrought iron and steel are easily corroded when exposed to moisture. The iron oxide is not particularly

[illegible]

harmful about the conductor, since it has a fairly good conductivity and absorbs and retains moisture.

Cast iron is very little affected by oxidation, and being relatively cheap, allows the use of heavy sections in grounding plates which would be prohibitive in the case of copper.

Copper, under ordinary conditions stands corrosion fairly well, but certain soils have chemicals that corrode it rapidly. For this reason, copper plate grounding devices or simply "grounds" should be periodically inspected and tested.

Zinc is hardly affected by oxidation under ordinary conditions.

The desirable characteristics of grounding conductors in the apparent order of importance are:

1.-- Section of maximum periphery.

2.-- Material of high conductivity.

3.-- Material of high resistance to corrosion.

4.-- Path as nearly straight as practicable.

When a conductor discharges a high frequency current and "skin effect" takes place, its effective conductivity is approximately directly proportional to its periphery, regardless of the net cross-sectional area. From this point of view, circular cross-section conductors are, evidently, the most undesirable for grounding purposes. A hollow section, however, such as a pipe, is particularly well adapted for such use, since its external periphery is con-

paratively large in proportion to its cross-sectional area. Flat metal strips are also satisfactory, although the density of the high frequency current is decidedly greater at the extremes of the section.

A number of special sections are on the market which offer slight advantages over pipes and flat strips.

The conductivity of the material is not of very great importance when phenomena such as "skin effect"enter into consideration; so that the use of copper for grounding purposes, in the average case, may be considered as a luxury from an economic standpoint. There are cases, however, where the importance of the ground connection warrants large expenditures to insure adequate protection. In such cases copper conductors should always be used.

Ground conductors and connections should be of such a material as will resist corrosion and deterioration. Corrosion may reduce the effective area of the conductor to such an extent as to greatly affect its conductivity and even destroy it.

By galvanization, a thin coat of zinc is placed over the surface of iron or steel which protects them admirably against corrosion. Galvanized iron pipe or strip have thus all the desirable characteristics of good grounding conductors. Care should be taken not to bend either pipes or strips very sharply because the zinc coating may come off, leaving the surface of the iron exposed to oxidation. Sharp bends in the conductor are also objectionable because they create

accumulations of magnetic flux, causing an increase in the inductance and consequently in the total impedance of the conductor and limit, therefore, its discharging capacity.

The relative location of lightning conductors with respect to those of the power system deserves very particular attention.

The electromagnetic induction on wires paralleling lightning conductors has often been the cause of considerable damage. Cases are cited where the insulation of apparatus has been punctured by the induced potentials of heavy lightning discharges. Rolling equipment, on account of its usual wiring complications, is highly susceptible to this kind of troubles.

Where grounding conductors are exposed to traffic of any kind, they should be protected with some non-conducting material, such as wood, for at least 7 feet from the plane of the ground. Such insulating guards not only protect the conductor from deterioration, but also serve to protect the people or animals that may happen to be near the conductor in the case of discharge. In places where the traffic is dense, it is desirable to paint conductor guards some color indicating danger, so that people may be aware of them especially during storms.

Grounding devices may be subdivided into three general types: pipe grounds, plate grounds and special or patent grounds.

PIPE GROUNDS

A pipe ground consists generally of a piece of iron pipe driven several feet into the ground and connected at its upper end to the ground conductor. The size of pipe generally used for these purposes varies from 3/4 to 2 inches and the depth to which the pipe is driven varies with the nature of soil and the importance of the ground connection.

In soft soil, containing considerable moisture, a pipe may be driven 10 or 12 feet without any difficulty; but in soil containing coarse gravel, several trials may be necessary before the pipe can be driven to a desirable depth. In cases where the ground is exceptionally hard, it is advisable to start the hole with a steel bar and then insert and further drive the pipe. Pipe grounds are of course out of the question on rocky soils; there a different type of ground should be used.

The essential presence of moisture about ground connections renders the conduction of electricity through them a purely electrolytic process, which like any other of its kind, requires the aid of an electrolytic agent to perform its normal functions.

Moisture, by itself, is a poor conductor. The moisture retaining qualities of substances such as charcoal or coke, makes them desirable in the neighborhood of a ground connection only when acting in conjunction with some electrolytic agent such as common salt or washing soda,

salt being preferable, since it has little or no destructive action on the pipe. Moisture, with these substances in solution, should always exist about the surface of the conductor in order to have a reliable connection.

The use of steel points at the lower end of ground pipes is advisable. There are two kinds of points that are especially fitted for two kinds of connections.

For connections where a good ground is not essential, a point should be used whose maximum cross-section should not exceed that of the pipe; in order that the contact between soil and pipe be as large as possible. Such a ground does not require the use of any electrolytic agent.

On important grounds, however, where salt or any other agent is required, points of cross-section larger than that of the pipe should be used in order to leave sufficient space around the conductor for the electrolytic agent, which in such cases should be dissolved in water and the solution poured in. Grounds of this type are very satisfactory and are cheaply constructed. There are, however, other methods of obtaining good results.

A 2 or 2-1/2 inch pipe is driven into the ground to a depth of 5 or 6 feet, then pulled out, and the hole filled with rock salt. A piece of 3/4 or 1 inch galvanized iron pipe about 12 feet long is then driven through the 5 or 6 feet of salt and about 5 feet more into the ground. The top of the pipe is then cut off and threaded and an additional piece, to suit the particular conditions,

is screwed to the ground pipe.

A one inch galvanized iron pipe about 6 feet long is driven 5 feet or so into the ground, then the end is cut off and threaded and an equal length is screwed on, with a suitable coupling, and driven 5 or 6 feet further. Cutting the pipe in two serves for two purposes: first, to facilitate driving, and second, to slightly widen the hole by means of the coupling and the vibration of the pipe caused by the hammering. This space is then filled with a saturated solution of salt. An additional improvement is made by digging a reservoir-like hole around the pipe, about one foot deep and 8 or 10 inches in diameter and partially filling it with rock salt to a depth of about 8 inches. Care should be taken to dig this reservoir after the original hole has been filled up with salt or else before the pipe is driven.

By either one of these methods, resistances to ground can be obtained as low as 6 ohms, if conditions are favorable.

The presence of grease on the surface of any ground connection is highly undesirable and pains should be taken to keep pipes, plates, etc. clean when put into the ground.

PLATE GROUNDS

Plate grounds generally consist of wide strips of copper plate buried in the ground and having a substantial

connection to the discharge conductor.

The electric conductivity from plate to ground is roughly proportional to the exposed area of the plate, with some restrictions, however, so that its shape shall be such as to have the least possible self induction. This is a very essential point that is sometimes overlooked by designers. There have been people who recommend the use of long plates rolled in the shape of a choke coil, thinking perhaps to have discovered a very desirable shape, on account of the large surface exposed for the size of the hole necessary to put the ground. As a matter of fact, such a plate would act like a choke coil and reflect the outgoing waves back to the line, thus rendering the arrester not only useless but harmful.

Before plates were thought desirable for grounding connections, the recommendation of "a few turns of heavy wire embedded in charcoal" was very common. It is useless to discuss the absurdity of such a practice.

A common size of copper ground plate is 3 feet by 3 feet by 1/32 inch thick with a heavy conductor well soldered all along one center-line.

The use of charcoal or coke for embedding the plate is advisable especially when in combination with powdered common salt.

The ground conductor should always have as little curvature as possible for the reasons already discussed.

Copper plates, when placed in certain soils, are subject to rapid deterioration, therefore, they should only

be used when pipe connections are impracticable.

SPECIAL GROUNDS

The special or patent types of ground connections consist in general of more or less ingenious combinations of moisture retaining substances and suitable conductors with sufficient exposed area to deliver the charges to ground. These devices behave very much like the combinations of metal and charcoal already discussed with the exception that they may be perhaps more easily installed and attended to in case of trouble.

The use of cast iron plates for grounds is becoming very general on account of the satisfactory characteristics of such plates when placed in service:

1.-- Plates embedded in charcoal or coke with a good electrolytic agent, have very low resistance.

2.-- Plates are cheaply installed, especially while erecting the pole line, by using the same holes.

3.-- They have a relatively long life, under normal conditions.

4.-- They are relatively cheap.

The number of ground connections that should be installed in a station or substation must correspond with the number of independent circuits, so that disturbances shall not have a direct path from one circuit to the others. Therefore, each of the following protective circuits should have a separate

ground connection:

1.-- Building lightning rods.

2.-- Transmission line lightning arresters.

3.-- Feeder lines lightning arresters.

4.-- Transformer groundings.

5.-- Generator groundings.

6.-- Rotary converter groundings.

7.-- Auxiliary apparatus groundings.

It is desirable that groundings of different circuits should be placed as far apart as practicable in order to avoid any possible interference.

The lightning rods protecting the building are grounded to either pipes or plates located directly under the vertical leads.

The transmission line lightning arresters are usually grounded to a large plate of six to nine square feet of exposed area. Either cast iron or copper plates are used for this purpose. When cast iron plates are used, the ground conductor consists usually of a 1-1/2 or 2 inch galvanized iron pipe screwed into a properly threaded hole in the plate. This pipe usually projects up the ground a few feet and the connections are made to the pipe through a specially designed brass cap where all conductors should be soldered.

Station equipment is usually grounded to simple pipe or plate grounds.

In any case, ground connections should be placed where they can be easily inspected and tested.

ELECTRIC RAILWAY GROUNDS

Lightning arresters for the protection of electric railway distribution systems are grounded either to the rails, to an independent ground or to both rails and ground.

Grounding to the rails only is objectionable. There are frequent cases on interurban and other lines in which the rails are practically insulated from the ground by the rock or gravel ballast commonly used. Under such conditions, grounding to the rails simply serves to transfer the charge from the line to the rails when the arresters operate. The sudden rise of potential of the rail at any point causes a similar effect on motor cases and other apparatus with grounded frames. This sudden strain may puncture the insulation and cause considerable damage to the equipment. The sudden rise of potential of the car frame also endangers greatly the lives of the crew and passengers. Consequently, this practice is highly undesirable and should be avoided at any cost.

Connecting to an independent ground has also its serious objections. Taking the same conditions as in the previous case; electric charges may be induced on both trolley and rails by passing clouds or cloud discharges. In any case, should the line arresters operate, the voltage of the trolley wire and of trolley poles on cars would be momentarily reduced to earth potential and all the electrostatic energy stored in the rails would be discharged to ground through the car equipment causing damage varying with the severity of the

discharges and the stored energy in the return system. The car frame as a whole, would be subjected to dangerous variations of potential as in the previous case.

In the third case, however, the rails are kept continually at earth potential, so that discharges can flow only from the trolley down, thus encountering the car protective apparatus which leads them to rail and consequently to ground. Such a system is, therefore, as far as lightning protection is concerned, the most desirable; unfortunately, it is not applicable to every case. The committee on "Lightning Protection" of the American Electric Railway Engineering Association recommends such a practice except under the following conditions:

1.-- Where the current flow on the connection from the track rail to earth would exceed an average of 1/4 ampere during any twenty-four hour period; this average being determined by considering the algebraic sum of the currents.

2.-- Where alternating current track block signals of the double-rail type are used.

Where the foregoing exceptions exist, and in order to prevent doing away with the rail connections, it was suggested that the connections be made from the line lightning arrester to both earth ground and track rail but that there should be installed in the circuit between the point where the rail connection joins the lightning arrester and the earth ground itself a suitably designed air gap. The committee thought that under such conditions it would be perfectly safe to make

the solid connections to both rail and earth without the air gap but had not sufficient information from signal manufacturers to warrant endorsement of the recommendation.

C H A P T E R V

TYPES OF PROTECTIVE APPARATUS.

APPARATUS USING THE SPARK GAP

In 1717 Reiman, a Pole, saw lightning run along iron rods without injuring them but shattering the stone between. This was the pioneer idea that led to the use of a conductor as a free path for electrical discharges. Franklin, who was perhaps aware of this fact before trying his kite experiments, made the first practical use of the principle when he invented the lightning rod.

It was not until 1846 that Steinheil devised the first protective apparatus. It consisted of two large brass plates separated by a thin layer of silken material. This apparatus was intended, by its inventor, to protect the two wires of a line against lightning discharges. Curiously enough, the plates were each one connected to a line wire and grounding was not at all considered. However, this was the start of a long series of developments.

Meissner was the first one to think of grounding one plate while Siemens used this principle in the first commercial form of lightning protector known as the "Siemens Plate Protector", which consisted of nothing more than the original plates separated by a thin film of air; one of them was to be connected to the ground through a certain resistance, and

the other to the line.

Bregnet was probably the first to utilize the fusibility of a fine metal wire for protection of apparatus,

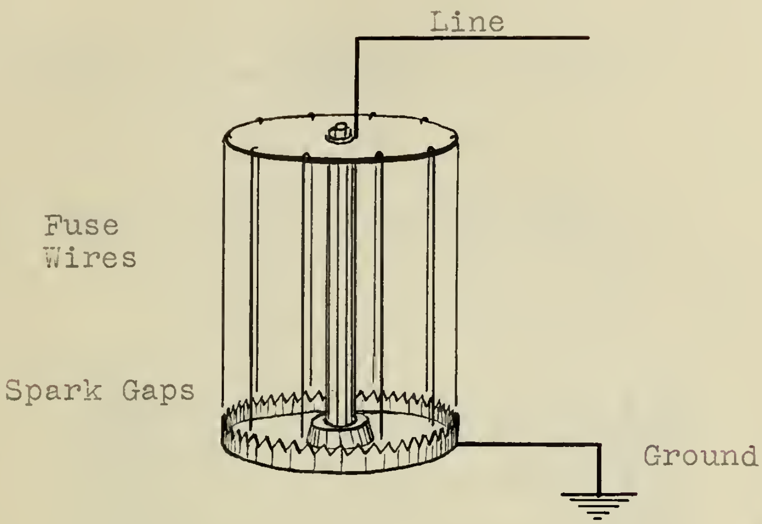


Fig. 7.-- The "Bright" Protector.

while Walker and Fardley combined both plates and fine wire and added sharp points between the plates as early as 1847. This protector operated very satisfactorily but required replacement of the fuse after every discharge.

Sir Charles Bright, trying to overcome this trouble, invented a very ingenious combination of points and fine wire, so that the protector remained in perfect working order even after a succession of discharges. It consisted of a round brass plate toothed as shown in Fig. 7, with an insulating post which supported another plate of the same diameter. Fuse wires could be hung from the top plate with such a length as to leave the desired spark gap to the base plate. After

each storm, all the fused wires had to be replaced, not without disconnecting the arrester.

Fig. 8. "Ajax" Arrester Unit.

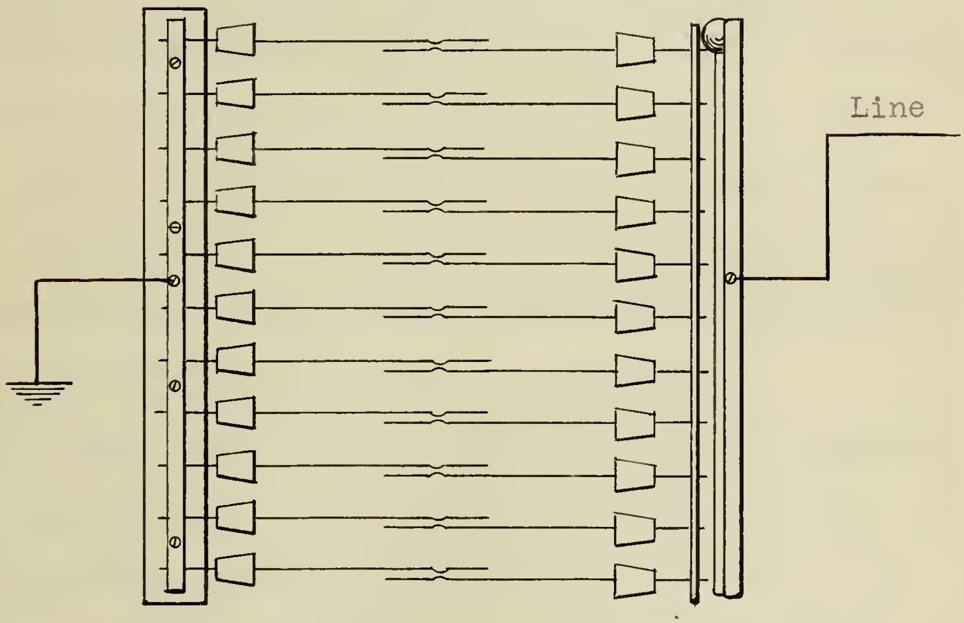


Fig. 9.-- "Ajax" Lightning
Arrester.

This arrester operated so well in the low current systems where it was employed that for many years it was very slightly developed.

There is still a lightning arrester on the market, based on a very similar principle. Fig. 8. shows one arrester

unit. It consists of two three inch pieces of brass wire with a single insulation, which enter a glass tube and are sealed in position therein. Within the tube the wires are bent as shown in the figure so as to get the desired length of air gap, this distance being determined by the working pressure of the system to be protected. Sealed and insulated in this manner, the air gap is unaffected by atmospheric conditions and thus always presents a path of uniform resistance to the static discharge. The fuse wires connect directly to the gap.

The arrester proper consists of eleven such fuses connected as shown in Fig. 9. The carbon ball C connects automatically only one fuse at a time to the line. When one fuse is blown off, the ball will descend and immediately connect the next fuse to the line. The blown fuses should be replaced as the storm ceases. The scheme is simple and effective but requires a good deal of attention.

The choking effect of coils to lightning discharges was discovered by Varley about 1871. On applying this principle to telegraph apparatus, by twisting the ends of the line wire into the shape of a coil, he found it a very efficient protector for moderate discharges, but the heavier discharges burned not only the coils but the receiving apparatus as well. In trying to overcome this difficulty he developed the so called "Lightning Bridge". This apparatus consisted of a gap, about .05 of an inch, between two brass needles embedded in powdered charcoal. The "Bridge" was shunted to the instruments to be protected; but it often happened that the

particles of charcoal between the needles became polarized and the protector acted as a short circuit on the instrument.

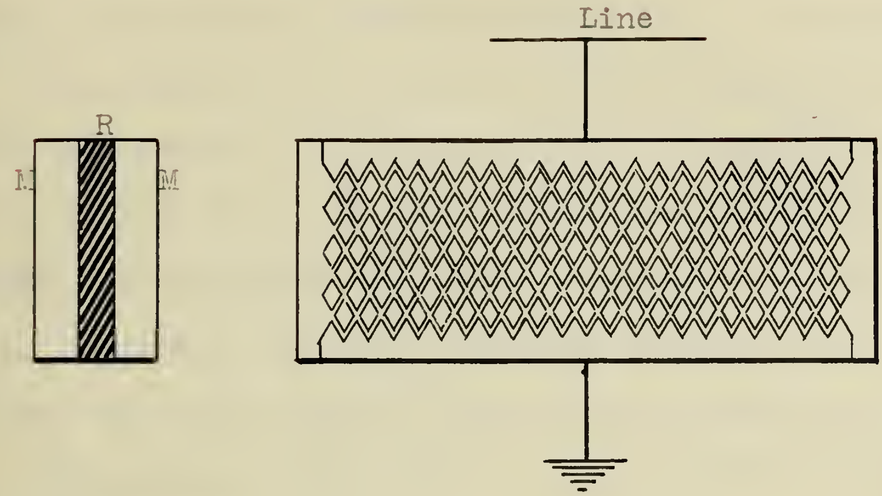


Fig. 10.--"Mirror Plate"Protector.

Varley also developed the "Varley Vacuum Protector" which consisted of a partially exhausted glass tube with two needle point electrodes. This device was to be used for protecting submarine cables against excessive potential rises and oscillations; but it was found that this kind of protector even aided the formation of disturbances in the cables. The protector was redesigned later but without improving its operation very materially.

A new type of arrester appeared about this time, called the "Mirror Plate Protector". It consisted of two silvered mirror strips M, M, Fig. 10, placed against a hard rubber

plate R. The silvering was cut into small quadrangles, thus making a great number of gaps and paths between the upper and lower strips of the silvering. The upper strip was connected to the line and the lower to the ground with or without series resistance. This protector embodied the first idea of the multigap and multipath arresters which will be discussed later.

The arresters previously described gave more or less satisfactory results in protecting the low current systems where they were used. As power transmission started its development, it was found that such apparatus did not afford adequate protection for the transmission systems on account of holding the arc after the high tension discharge occurred.

The problem, from then on, was to find schemes to suppress the arc of dynamic current that followed the discharges. A few of these schemes will be described here very briefly.

The "Comb" arrester is representative of a type then developed, which aims to solve the problem by lengthening the gap by means of a suitable mechanism. The arrester consists of a coil (Fig. 11) connected to the line and to a moving lever which operates a comb-shaped gap, the fixed side of which is connected to the ground.

This type of arrester was found unsatisfactory on account of the choke coil effect of the electromagnet, but the problem was given a solution by shunting the coil with a non-inductive resistance or a gap, so that the high frequency current would pass through the latter in preference

to the coil. The dynamic current would choose the low resistance coil and operate the arc-breaking mechanism. This was

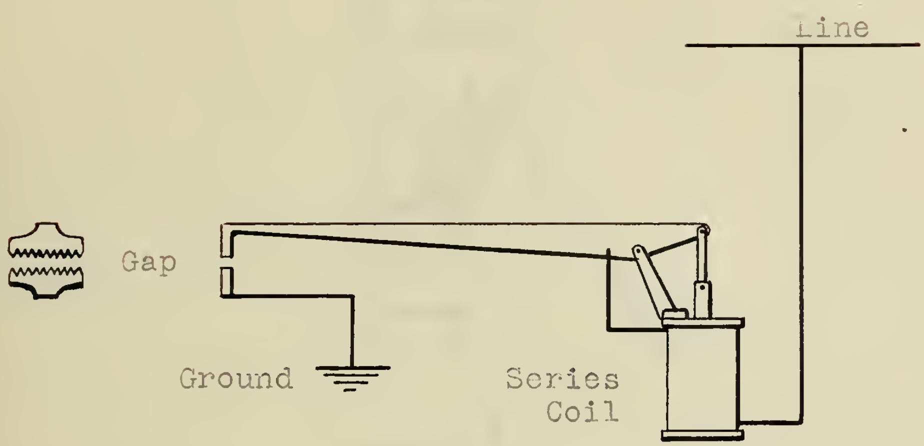


Fig. 11.-- The "Comb" Arrester.

a very important step in the development of protective apparatus.

Others have solved the problem by putting two gaps in series and shunting the electromagnet across one of them.

The "Wood" arrester represents this type of protective apparatus. Some of these arresters are still in use in a few out-of-date plants.

The "Wood" arrester consists of a moving lever L (Fig. 12) pivoted at A and operated by the plunger of the electromagnet M. Both of the gaps are dentated or comb-shape

in order to subdivide the arc so that it can be more easily extinguished. The high tension discharges pass directly to

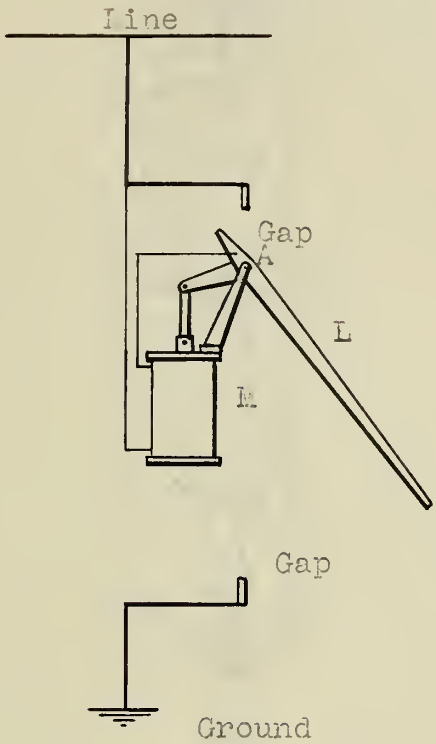


Fig. 12.-- The "Wood" Arrester.

ground through the gaps and lever arm but the dynamic current invariably chooses the path through the coil and operates the breaking mechanism.

The inertia of the moving parts of this arrester is too large and the frequent simultaneous operation of arresters, on both sides of the line, cause occasional severe short circuits of considerable duration. This bad characteristic of the arrester led to lighter construction and to the introduction of a certain amount of resistance between the arrester

and ground. This resistance improved its operation somewhat but at the same time it limited the discharge. The inertia

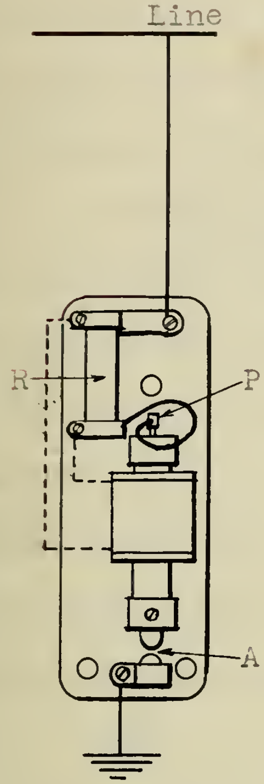


Fig. 13.- Garton-Daniels Low Voltage Lightning Arrester, (350 Volts and Less)

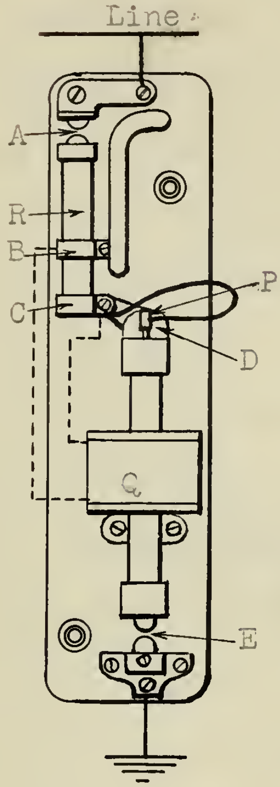


Fig. 14.- Garton-Daniels Medium Voltage Lightning Arrester, (1,200 to 2,500 V.)

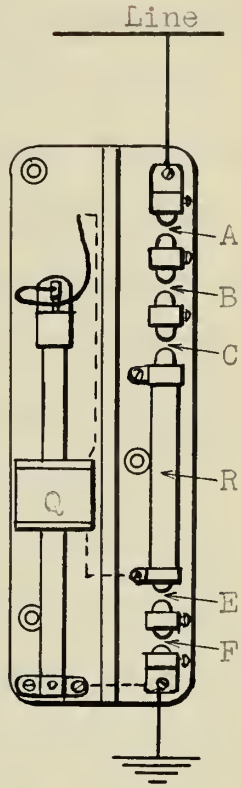


Fig. 15.- Garton-Daniels High Voltage Lightning Arrester, (Up to 3,500 Volts)

of the moving parts was still too great and many schemes were tried without much success until finally the "Garton-Daniels" arrester was put on the market.

The particular feature of the different types of "Garton-Daniels" arresters is the plunger type of spark gap operated directly by an electromagnet shunted to a resistance rod or to gaps in the discharge circuit.

The low voltage (up to 350 V.) type of arrester consists of a resistance R, Fig. 13, in series with the plunger P whose lower end is in loose contact with the upper electrode of the spark gap A. The lower electrode of the gap is connected directly to the ground. The plunger, in rising, creates a gap whose length varies with the value of the current flowing through the coil. The rapidity of application of the magnetomotive force gives the plunger an impulse which carries it high enough to extinguish the arc of the dynamic current. When the discharge occurs, it follows the direct path, through the resistance, plunger, gap and ground conductor, but the dynamic current will choose the path through the coil and cause its own extinction by the motion of the plunger. The 350-1,200-volt arrester is not shown.

Fig. 14 illustrates the arrangement of apparatus to protect circuits of voltages ranging from 1,200 to 2,500 volts. In this case, the discharge will follow the path through gap A, resistance R, copper strip D, plunger P and gap E to ground. But the dynamic current flows along the same path with the exception that instead of using the portion of resistance B-C as its only path, it flows mostly through the low resistance coil Q which, in turn, lifts the plunger and extinguishes the arc.

The high voltage arrester consists of the series gaps A, B, C, E and F (Fig. 15) with the resistance R inserted as shown in the diagram. The plunger coil is shunted across the last two gaps and is connected in series with the plunger

itself. The dynamic current tries to follow the same path, but in reaching E, the path through the coil and plunger offers the current less impedance than the shunted resistance, consequently a large portion of the dynamic current flows through the coil and causes its own extinction.

All "Garton-Danicls" arresters work on the same principle for both direct and alternating current. Slight modifications, however, make them more adaptable to conditions under direct and alternating current circuits.

This type of arrester is giving fairly satisfactory results, but the increment of time required for successive operations is often-times too great to afford the desirable protection against multiple discharges. Multiple discharges have been recorded in which as many as 48 strokes occurred in .625 of a second. Consequently, any arrester requiring for its operation an interval of time of appreciable length, cannot afford satisfactory protection against multiple discharges.

Other protective apparatus, involving a time element for their operation, have been constructed on different principles.

The "Windsor- Wurts" arrester utilizes the expansion of the air, when subjected to the high temperatures of the arc, to operate a simple mechanism which ruptures the arc itself. The apparatus consists of a metal gap A (Fig. 16) shunted with a carbon ball C resting on the electrodes by gravity and free to move along the tube T which is provided

with vents H at its upper end. Gap A is in series with gap B in chamber D. When the line voltage exceeds a predetermined value, the gap B breaks causing the sudden expansion of the air in chamber D. The expanded air flows directly through gap A, causing the carbon ball C to rise

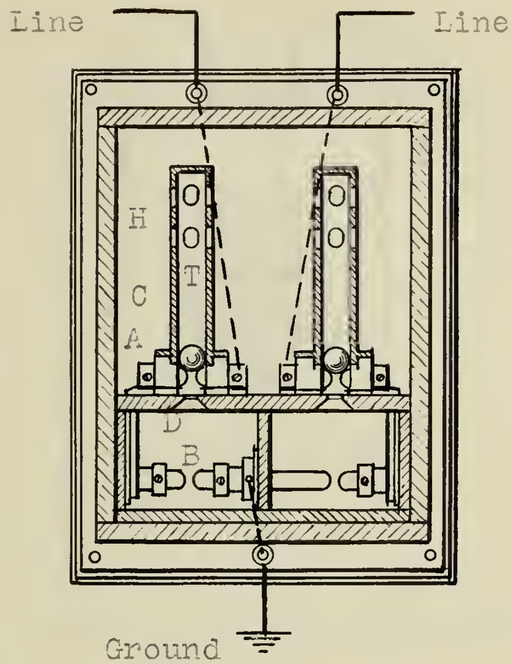


Fig. 16.--The "Windsor-Wurts"
Lightning Arrester.

thus striking an arc and lengthening it to extiction. The ball reassumes the normal position immediately after the discharge. If another lightning discharge occurs while the ball is at the top of the tube T, it is easily discharged through the gaps A and B in series. The first discharge has only gap B to ground and the others, immediately following it, have gaps A and B in series. But the state of ionization of the air in the gaps allows discharges to

occur at lower voltages and thus compensates for the increased gap, so that this arrester can take care of any number of successive discharges effectively.

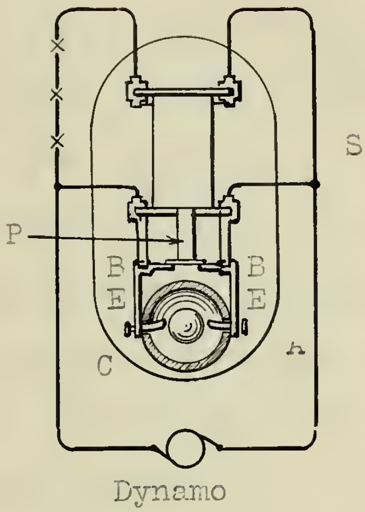


Fig. 17.- Lightning Arrester
for Series Circuits.

The "Windsor-Wurts" arrester was especially adaptable for use in alternating current circuits of about 1,000 volts but it could not be used for either arc or 500-volt direct current railway circuits.

An arrester based on the same principle was then devised for arc circuits. It consisted of a chamber A (Fig. 17) made of some insulating material and containing in its center a carbon ball C. The electrodes E, E, pivoted at B projected into the chamber through suitable holes, leaving the desired gap with the carbon ball. The electrodes were

directly connected across the terminals of the generator and the solenoid S was connected in the series circuit. A plunger P, operated by the solenoid, was so arranged as to allow the electrodes into the chamber only when the solenoid was energized and to push them apart when not so. The action of the arrester was very simple: When the line was in operation, the plunger was pulled up and the electrodes allowed to form the desired gap with the carbon ball. Should lightning strike the line, the simultaneous action of the two gaps would cause a short circuit on the generator and line. Consequently, the solenoid would release the plunger spreading the electrodes and breaking the arc. The system would reassume its normal conditions immediately after.

The chamber A was originally intended to act as a pressure chamber so that the hot air in it would expel the electrodes after the discharge, but its unreliable operation forced the designers to add the solenoid S and thus complicate the connections considerably.

But neither of these two arresters was capable of protecting 500-volt direct current circuits. The same principle of air expansion was used in the design of an arrester for this service. The arrester is called the "Pick-Axe" on account of the shape of the moving arm. It consists simply of a curved carbon (Fig. 18) protected from mechanical stresses by a metal sheath of the same shape, fastened to the reciprocating arm A. The curved carbon forms a gap with the grounded terminals B, B, in either of the chambers.

Its operation is as follows: when a discharge occurs on the line and the potential to ground exceeds the safe limit, the gap

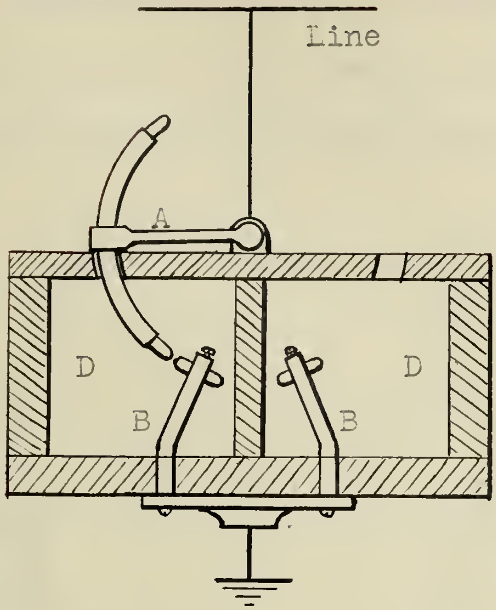


Fig. 18.--The "Pick-Axe"
Lightning Arrester.

breaks, thus causing a momentary short circuit on the line. The expansion of the air in the chamber forces the curved carbon into the other chamber extinguishing the arc. The arrester is then ready for the next discharge. This type of arrester gave satisfactory operation but was very easily put out of adjustment by the severe mechanical stresses to which it was subjected. The least binding of the carbon against the walls rendered it inoperative. In later redesigns, the double pointed arm was replaced by two single pointed ones which normally assumed the vertical position, as shown in Fig. 19. In these arresters, the ground connection was made to one of the carbons and the line connected to the other.

These arresters were found unsatisfactory when placed on cars, due to the jarring which caused the arms to swing varying the gap continually and thus rendering the arrester inoperative a great part of the time. On this account, the arrester was redesigned with slanting side walls, thus producing

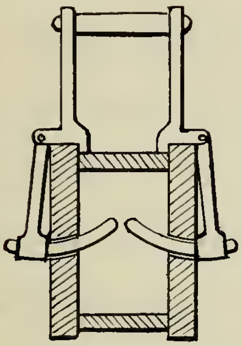


Fig. 19.- Modified Form of "Pick-Axe" Arrester.

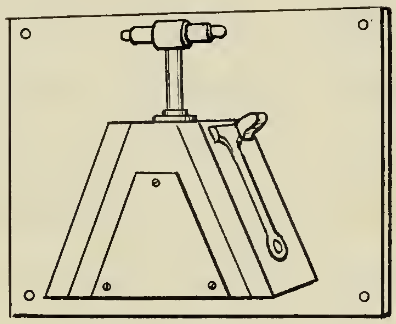


Fig. 20.- "Keystone" Lightning Arrester.

the "Keystone" lightning arrester shown in Fig. 20.

About this time (1892) it was the general practice to install the protective apparatus at the stations only and to depend on their performance to save the line from damage by lightning disturbances. Naturally this was far from being the case and the damage done by lightning was consequently increased with the length of lines. It was thought then to install simple spark gaps with carbon electrodes at frequent intervals along the lines and install at the station an overload circuit breaker which would automatically close

itself a second or so after the overload occurred. Experimental gaps and circuit breakers were installed but unfortunately gave the following result: as soon as the gap operated, the circuit breaker opened and the spark in the gap ceased but the electrodes were left at so high temperatures that the arc was reestablished by the closing of the circuit breaker. On this account it was sought to experiment with gaps of metal electrodes.

The experimental line was a single phase, 1,000-volt, alternating current connected to a small alternator. Brass was arbitrarily chosen for the first experiment. The gap consisted of two pieces about 1.5 inches long and one inch in diameter placed side by side with a gap of about 1/32 of an inch. The arc was started by dropping a little bit of tin foil in the gap. It formed but immediately disappeared, not giving time enough for the circuit breaker to operate. This was a very remarkable performance and the reason for it was by no means evident. The experiment was repeated several times and always gave the same results. The nature of the electrodes then, seemed to be the cause of the interuption of the short circuit although the reason was not clear. When a larger generator was available, it was planned to experiment on it. Three large cylinders 3 inches long and 3 inches in diameter were then placed with the same 1/32 inch gaps, judging the small cylinders not big enough for the larger alternator. The experiment was a failure; the three big cylinders fused together. This was, of course, discourag-

ing. The small cylinders were then put to the test with very little expectation of remaining cylinders after the test. Very much to the surprise of the experimenter, Mr. A. J. Wurts, the short circuit was instantly interrupted with the formation of an arc no larger than was occasioned by the melting of the bits of tin foil and the brass cylinders were undamaged. The test was repeated with no different results. It was then concluded that while the mystery was still deep, it was evident that an important discovery had been made.

Evidently, therewas some radical difference between the large brass cylinders and the small ones and on inquiry, it was found that the large brass cylinders were made of bronze- an alloy of copper and tin- while the smaller cylinders were made of an alloy of copper and zinc. Apparently, the secret was in the zinc and to prove this, small cylinders of zinc were tested with satisfactory results; excepting that the discharges pitted them easier than those of brass.

Extensive investigations were then undertaken, which resulted in the discovery of some important characteristics of the metals and alloys henceforth called "Non-Arcing".

1.-- All monoatomic metals such as mercury, zinc, cadmium and bismuth possessthe non-arcing property.

2.-- Alloys with non-arcing metals seem to give better satisfaction than the pure metals.

3.-- Almost any shape of electrodes will work, exept parallel surfaces.

4.-- Gaps cannot be greater than 1/16 of an inch.

5.-- The most effective gap is between 1/64 and 1/32 of an inch.

6.-- Knurling the surfaces improves characteristics.

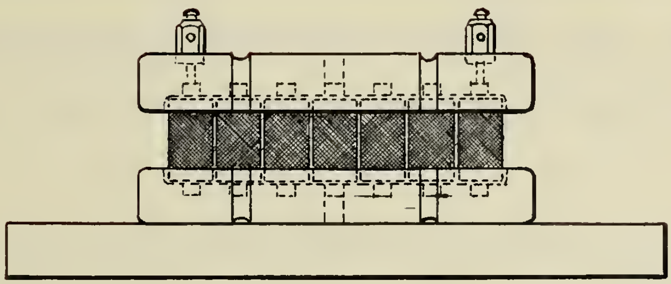


Fig. 21.-- Wurts Multigap Non-Arcing Metal Lightning Arrester Unit.

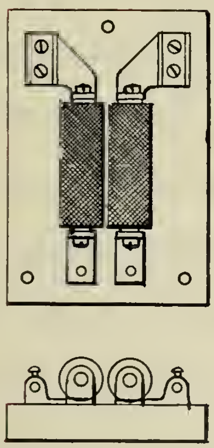


Fig. 22.-- Non-Arcing Metal Discharge Gap.

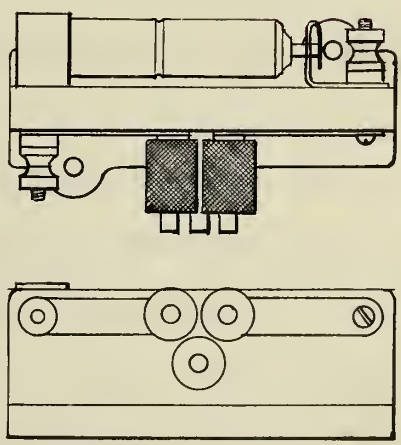


Fig. 23.-- Adjustable Gap and Vacuum Lightning Arrester Combination for Telephone Protection.

Commercial lightning arresters of this type consist of a series of zinc-brass cylinders with knurled surfaces, varying from 3/4 to one inch in diameter and from two to three inches in length, mounted on porcelain insulators. Fig. 21 represents a lightning arrester unit of this type.

A single non-arcing metal gap (Fig. 22) is often used to discharge accumulated static on electrical equipment such as transformers, generators, motors, etc. They are also used for tell-tale gaps in series with protective apparatus.

The three cylinder three gap arrester shunted with a vacuum arrester is shown in Fig. 23. This combination possesses two desirable characteristics: close adjustment (of the vacuum arrester), and practically unlimited discharge (of the non-arcing gap). Such characteristics make this combination particularly adaptable for the protection of low current circuits. The vacuum gap lightning arrester will be described later.

A careful study of the characteristics of the "multi-gap Non-Arcing arrester was carried on by Messrs. D. B. Rushmore and D. Dubois.# They explain the action of the metal cylinders as that of small condensers which are charged with varying amounts of potential, according to their distance from the line connection being maximum at that point and zero at the ground end.

#.--"Protection against Lightning and the Multigap Arrester. Pro. A. I. E. E. March, 1907.

Arcing between two successive cylinders consumes a certain amount of electromotive force. The successive losses in voltage thus incurred can reduce the discharge voltage between a certain pair of cylinders to such a value that no further discharge is possible between the remaining cylinders. A complete discharge takes place when the initial voltage is so great that the successive discharges do not bring it to a value less than that of the spark voltage, or when the drop across the gaps is so small that the sum is not sufficient to affect the initial discharge voltage.

The potential drop across any two consecutive cylinders depends upon the value of the current, which in turn depends on the capacities of the cylinders, or rather, on their capacity reactance. Consequently the current will be greater at high frequencies and the fall of potential between the first and second cylinders will therefore be less. As the arrester gaps break down successively, the fall of potential from one cylinder to another is less and therefore, such an arrester will discharge at a lower voltage for a high frequency than at a lower. In the same way that high frequency lowers the break-down potential of multigap arresters, by increasing the current of the spark, high resistance, by absorbing electromotive force when this current exists, decreases the break-down potential.

The use of resistance in series with multigap arresters has been the subject of many discussions. From our previous deductions, it is justly inferred that: since the series

resistance offers impedances varying directly with the frequency, the high frequency discharges, which tend to lower the break-down voltage by sending heavy currents, will be impeded in proportion to their frequency; while surges of low frequency will be hardly affected. Consequently, series resistance, if used effectively, will tend to equalize the break-down voltage and the discharge current at all frequencies. The use of series resistance also tends to increase the non-arcing power of an arrester, especially when used in combination with shunt resistances.

Arresters with such a combination of resistances are called "Low Equivalent Alternating Current Arresters" on account of their low spark equivalent and their adaptability to alternating current circuits. Fig. 24 represents schematically a low equivalent lightning arrester. When the arrester is not in action, the point P is at ground potential and, consequently, the arrester will discharge whenever the voltage at the point L of the line reaches a potential above the ground sufficient to cause the series gaps to break down. Thus, this action is independent of the number of shunted gaps. When the series gaps break down, the resistance between the points L and P is momentarily reduced to a very low value and nearly the full amount of potential is then impressed on the shunt and series resistances. If this abruptly applied potential is sufficiently high, the shunted gaps will be broken down. The generator current will then tend to follow; but the action of the gaps is such that only the first half

wave of the dynamic current will pass and the discharge will be suppressed at the end of this half wave.

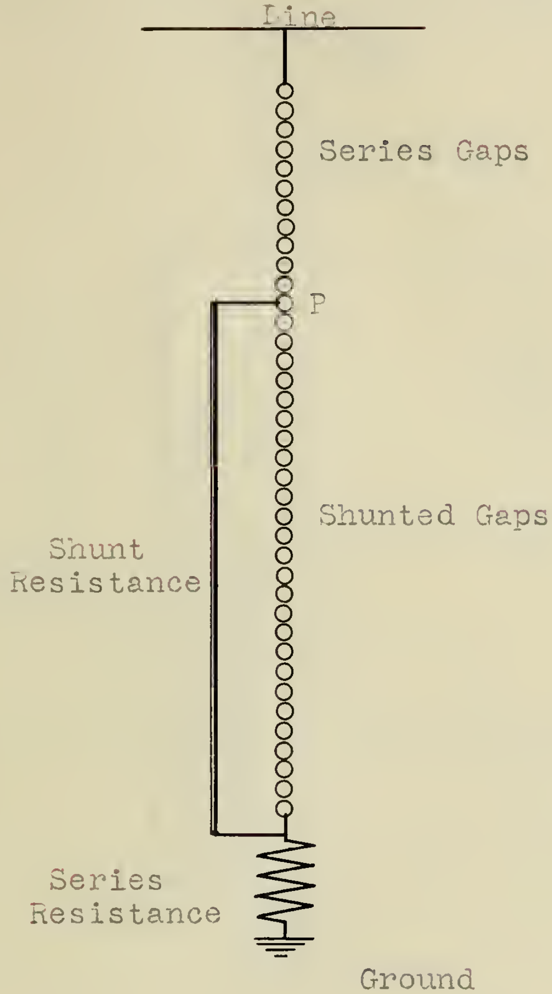


Fig. 24.--Low Equivalent Multigap Lightning Arrester with Single Shunt Resistance.

For circuits where very close adjustment is required, several resistors are shunted to the gaps as shown in Fig. 25. The behavior of this arrester is similar to that of the one already described although the combination of resistances renders the arrester more sensitive to minor disturbances.

The multigap arrester, with series resistance only, has also proved very satisfactory. There are several types of this arrester on the market. The Westinghouse type CR lightning

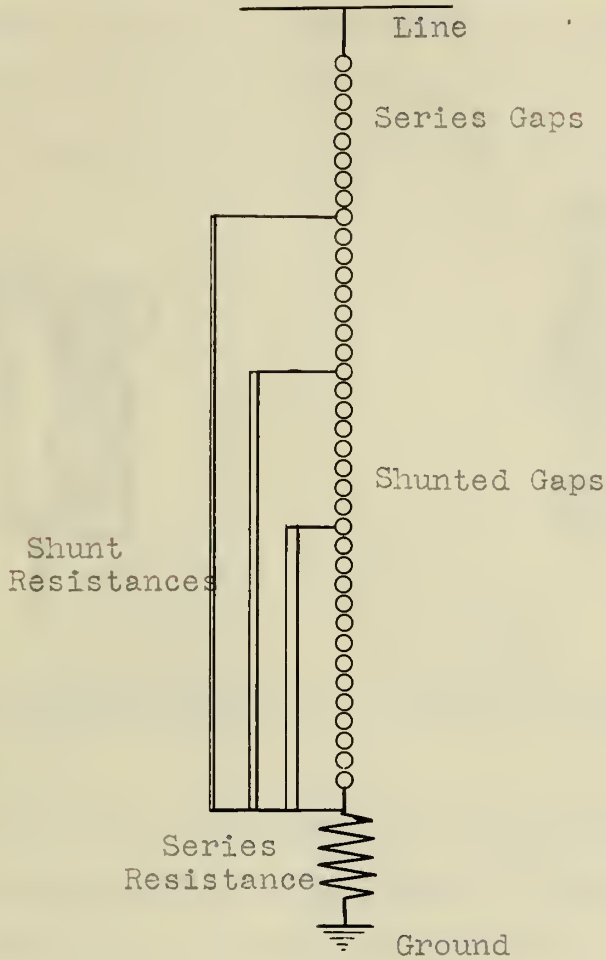


Fig. 25.-- Low Equivalent Lightning Arrester with Triple Shunted Resistance.

arrester shown in Fig. 26 consists of four non-arcing metal cylinders in series with a resistor and mounted on a porcelain base. The arrester unit is mounted on the inside front cover of the iron case, so that it is automatically disconnected from the circuit when the box is opened. This feature makes

inspection and repairs entirely safe. This arrester is adaptable to alternating current circuits of any frequency from 1,000 to 2,500 volts and unlimited capacity. For use on circuits from 3,000 to 6,600 volts, the same company manufactures type W, (Fig. 27) which is especially adapted for hanging on the line to be protected. It consists of a

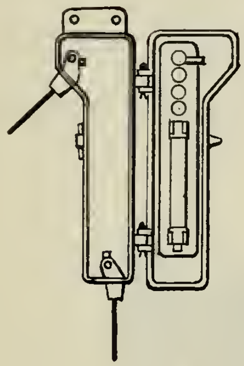


Fig. 26.-- Westinghouse Type CR Lightning Arrester.

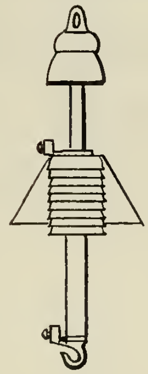


Fig. 27.-- Westinghouse Type W Lightning Arrester.

set of non-arcing metal cup-shaped discs mounted on a center insulating rod and forming arcing gaps between them. A resistor is connected in series and encased in a weather-proof micarta tube. An eye at the top of the arrester, insulated by a porcelain cap, allows the arrester to be suspended either from the line or from the cross arm. Two arresters in series can be used on circuits as high as 13,200 volts. For out-door service, the standard arrester is provided with an insulating shield, as shown in the figure, to prevent direct contact with rain or snow against the metal gaps. Non-arcing metal is used for these cup-shaped discs and their action is similar to that of the cylinders.

[illegible]

[illegible]

The arrester shown in Fig.28 represents another type of multigap arrester. It consists of a set of concentric non-arcing metal tubes shaped as shown in the figure. The porcelain caps are provided with grooves so located as to make all gaps 1/16 of an inch wide. Between these grooves there are sufficient perforations to allow free circulation of air through the gaps. The line is connected to the innermost cylinder and the earth to the outer one. The diverging gaps of the arrester allow the arc to be lengthened and extinguished.

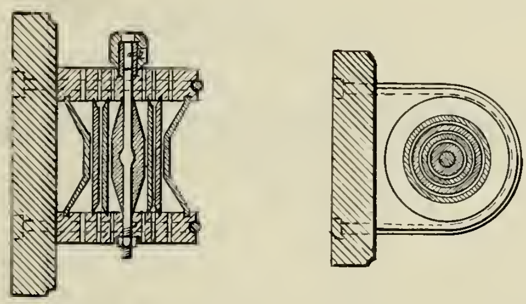


Fig. 28.-- The "S. K. C." Lightning Arrester.

The large amount of cooling surface greatly aids in this operation. At ordinary frequencies, about 5,000 volts are required to break the gaps but at frequencies of lightning discharges only about half of this potential is necessary. Consequently, the protection afforded by this type of arrester is a direct function of the frequency of the impressed voltage.

A type of multigap arrester based on a different principle, is being used in France with some success.

Fig. 29 shows the essential parts of this arrester: A series of brass discs are separated by non-combustible insulating discs of somewhat larger size and all mounted on

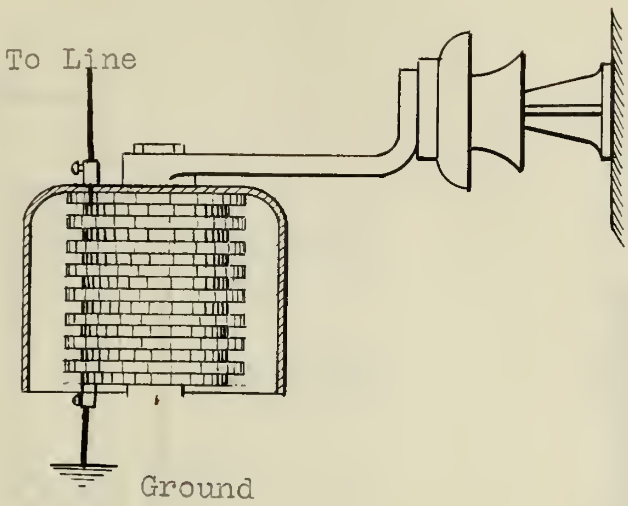


Fig. 29.-- Multigap Disc Arrester.

an insulating rod. The top metal disc is directly connected to the line and the bottom one to the earth with or without resistance in series. The suppression of the arc, in this case, is due to its subdivision into minute arcs, which exposed to the large cooling surface of the insulators are quickly extinguished. This arrester is only fitted for low potential circuits of less than 3,000 volts, alternating current.

The "Giles" arrester largely used in Europe is an ingenious modification of the Wurts multigap arrester. It consists of a number of independent multigap paths, each one fitted with a very high resistance (1,600 ohms) in series but the combination of so many such units, makes the effective

resistance of the arrester relatively small. This arrangement is shown schematically in Fig. 30. The gaps are formed by

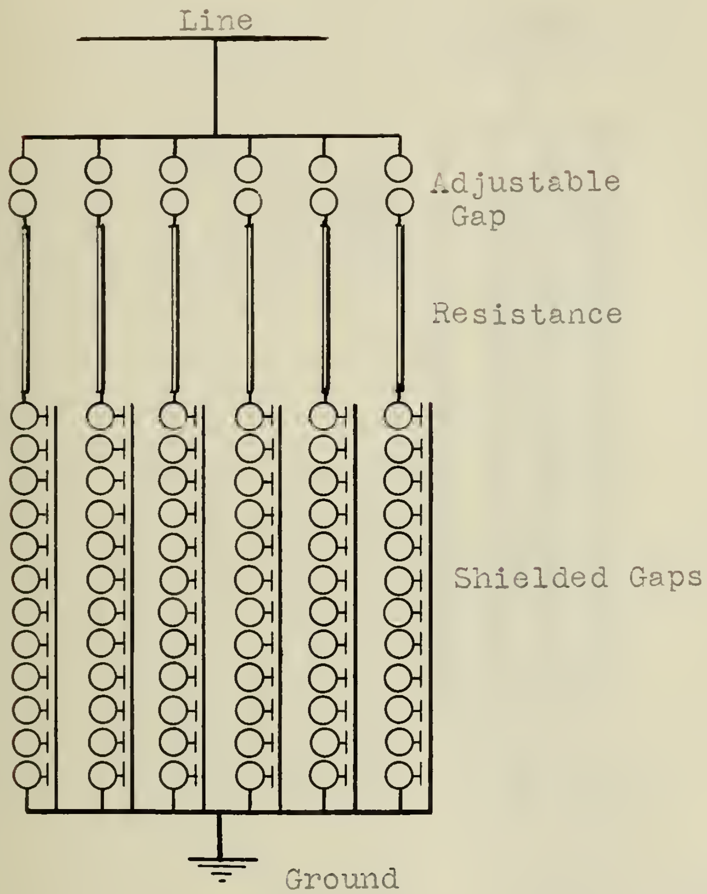


Fig. 30.-- The "Giles" Lightning Arrester.

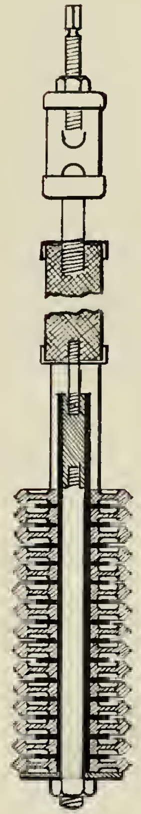


Fig. 31.-- The "Giles" Lightning Arrester Unit.

the rims of non-arcing metal discs, as shown in Fig.31, separated by mica washers and mounted on a hollow insulating arbor with a metal rod through it. This rod is electrically connected to the lowest disc and to ground, thus having a shielding effect on the gaps, not perhaps as effective as if it were placed on the outside on account of the "skin effect"

of high frequency discharges. The advantages of shielding the gap electrodes will be fully discussed later. The "Giles" arrester has given very good results on the low potential

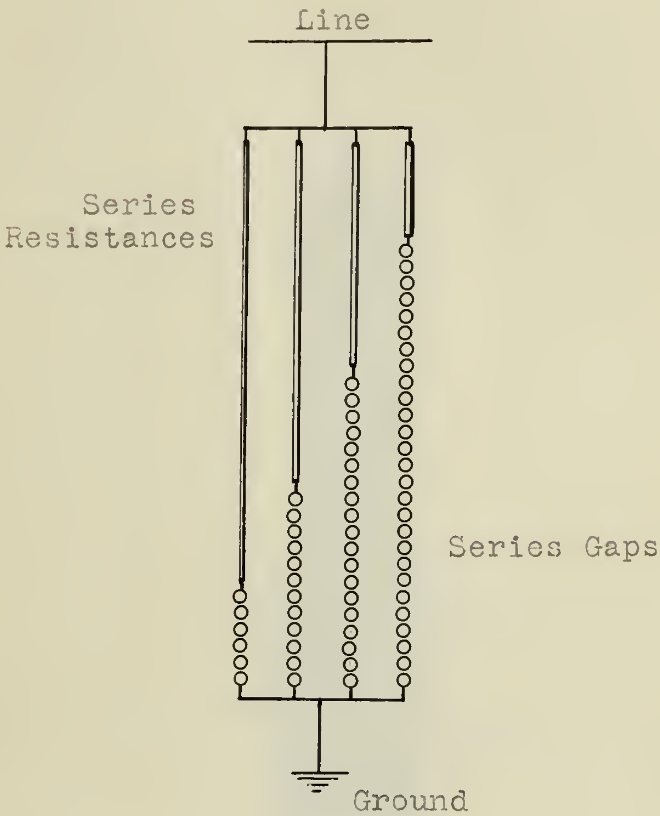


Fig. 32.-- Four-Path Multigap
Series Resistance Lightning Arrester.

circuits where it has been tried.

There is an American arrester based on similar principles. Fig. 32 shows its most essential parts, each of which has been previously discussed; the combination, however, deserves mention. When a high potential wave reaches the arrester, the first branch to discharge is that with the least number of gaps. If such a discharge is not sufficient to

keep down the voltage, the next branch will discharge and if the combined discharge is still insufficient, the next branch discharges, etc. The main advantage of this arrester over the regular low equivalent arrester is simply that in the

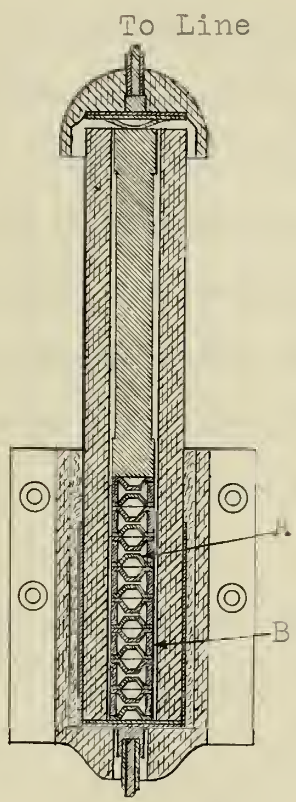


Fig. 33.-- "Compression Chamber" Lightning Arrester Unit for Low Potential Circuits.

former case, the discharge is distributed over a large number of gaps which are thus subjected to less intense discharges. This feature enables the arrester to maintain its non-arcing qualities even after the heaviest discharges. This is a very desirable characteristic which should be considered where

a high degree of protection is desirable.

The "Compression Chamber" lightning arrester shown in Fig. 33, is a multigap arrester involving some new principles in its operation. The non-arcing metal gaps are formed by the hat-shaped pieces A held in position by porcelain separators B. The lowest metal piece is connected to a fork-shaped antenna to which the ground conductor is soldered. The upper metal piece connects directly to a series resistance rod leading to the line. After the arrester is assembled, all openings are perfectly cemented as to form a hermetic compression chamber for gaps and resistance rod. The increase in pressure during a discharge, helps the gaps to maintain their non-arcing power even when subjected to very heavy discharges. The effect of the antenna shielding the gaps will be discussed later.

An improvement on resistance rods was accomplished with the development of this arrester. Fig. 34 shows a partial

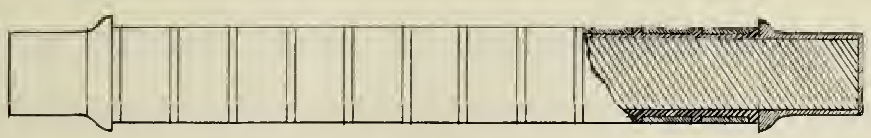


Fig. 34.-- Treated Carbon Resistor
Shunted by Metal Gaps.

cross-section of a resistor used with "Compression Chamber" lightning arresters. The resistor is inclosed in an insulating

tube moulded with brass rings at frequent intervals, so that at excessive drops of potential, these gaps break down and by-pass the resistor. Consequently, this arrester has a practically unlimited rate of discharge. Circuits up to 10,000 volts can be protected with this type of arrester. By placing

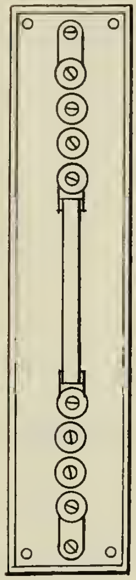


Fig. 35.--"Multigap Static Discharger".

a number of these units in series, higher potential circuits can be protected.

The Multigap Static discharger shown in Fig. 35 is a very useful application of the non-arcing metal gap. It consists simply of a series of gaps connected through a very high resistance. This apparatus, as its name implies, is fitted to discharge slowly accumulated static charges on circuits and it should never be expected to take the place of a lightning arrester. This discharger can be connected either from line to line or from line to ground.

The ability of an arrester to suppress or prevent the formation of an arc in its gaps, after a high frequency discharge, may be called its non-arcing ability.

The conditions afecting the non-arcing ability of a series of unshunted air gaps are of two sorts: First, those involved in the physical and chemical constitution of the electrodes and gaps, and second, those depending on the constants of the circuit to which the gaps are connected.

The conditions in the first class were fully discussed in the previous chapter. Those in the second class will be discussed here.

When the total power and the power factor of the circuit as a whole are kept constant, the number of gaps necessary to suppress an arc is somewhere nearly proportional to the voltage of the circuit. If the voltage, inductance, etc. are kept unchanged, the non-arcing ability is proportional to the short circuit current raised to some power between the first and the second, usually higher than 1.5. This law is not unexpected, assuming the cause of the holding of the arc in the gaps to be the heat generated by the discharge. This heat is proportional to the square of the current and to the resistance. But the resistance decreases with the increase in current. With a large current and a high power factor, the non-arcing ability is more nearly proportional to the first power of the current, but with small current and low power factor, it follows the second power very closely.

This law is of paramount importance as regards con-

ecial lightning arresters since the growth in size of central stations means that large currents flow on short circuits and consequently arresters require many gaps.

With a given current and a given voltage, the non-arcing ability varies approximately inversely as the inductance in the circuit.

The non-arcing ability is not appreciably affected by the frequency between the commercial limits of 25 and 60 cycles.

The magnitude of the arc in the gaps depends to a large extent on the instantaneous value of the voltage at the time of discharge. If the discharge occurs when the voltage wave is at zero, no arc will be formed in the gaps with any condition of inductance and capacity in the circuit, but the intensity of the arc increases with the instantaneous value of the electromotive force at the time of discharge.

The fact that the non-arcing cylinders of lightning arresters act as small condensers led to investigations concerning the effect of shielding the cylinders with metal conductors. The investigations were carried on by Mr. R. B. Ingram# and some of the results will be here briefly discussed.

When a gradually increasing potential is applied to a series of gaps such as those of a multigap lightning arrester, a point will be reached at which a spark will jump

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#--"Multigap Lightning Arrester with Ground Shields". By R. B. Ingram.- Elec. Jour., April, 1907.

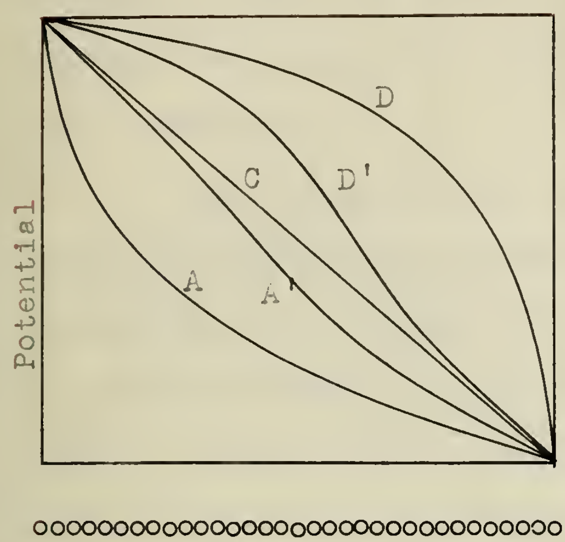
between the two electrodes in the series which have the greatest potential difference, other conditions being the same. The breaking of one gap, by reducing the number of effective gaps, throws higher stresses on the remainder and if the voltage remains constant the rest of the gaps will break in a quick succession. Consequently, the break-down of the arrester depends on that of the gap subjected to the greatest electrical stress.

If a curve is plotted between the number of gaps and their respective potential, taking one end of the series as a reference, the slope of this curve at any point represents the electrical stress at that point. This curve is called the potential gradient of the series of gaps. The shape of this curve depends on the conditions under which the arrester is tested. Fig. 36 shows a set of these curves. Curve A shows the potential gradient of a series of gaps with one end grounded. Under such conditions, the gap next to the line is the most severely strained.

The most desirable condition would evidently be to have the stress evenly distributed all along the gaps. Curve C represents such a theoretical case.

It was found experimentally that a shield placed near the cylinders changes the shape of the potential gradient curve very remarkably. If such a shield is placed the whole length of the arrester and connected to the ground, curve D represents the gradient. If the shield covers only part of the cylinders, starting from the ground end, the gradient

assumes the shape of curve D'; and if a short shield is connected to the line end, the gradient assumes the shape of



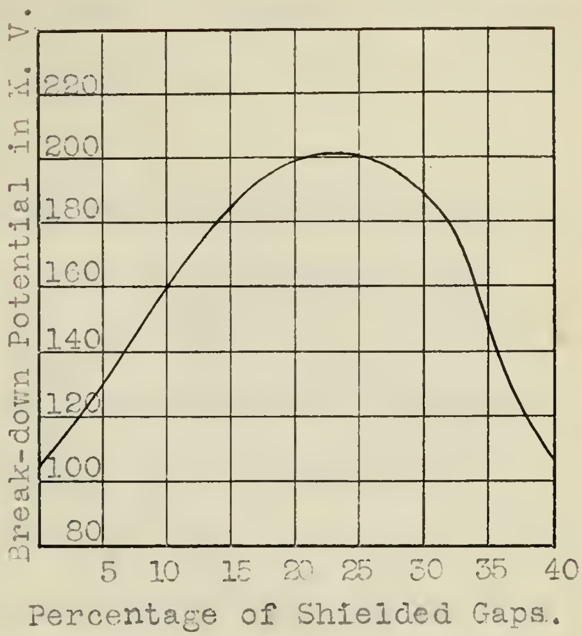


Fig. 36.-Potential Gradient Curves.

Fig. 37.

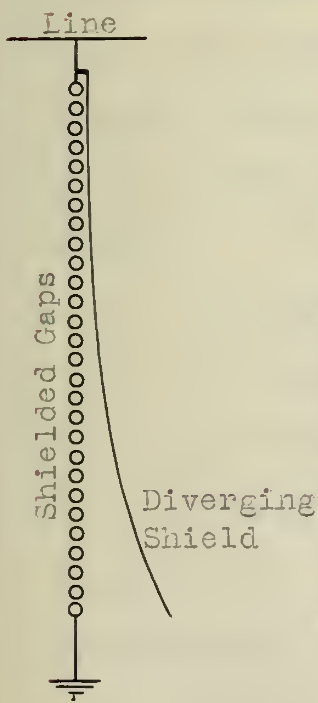


Fig. 38.

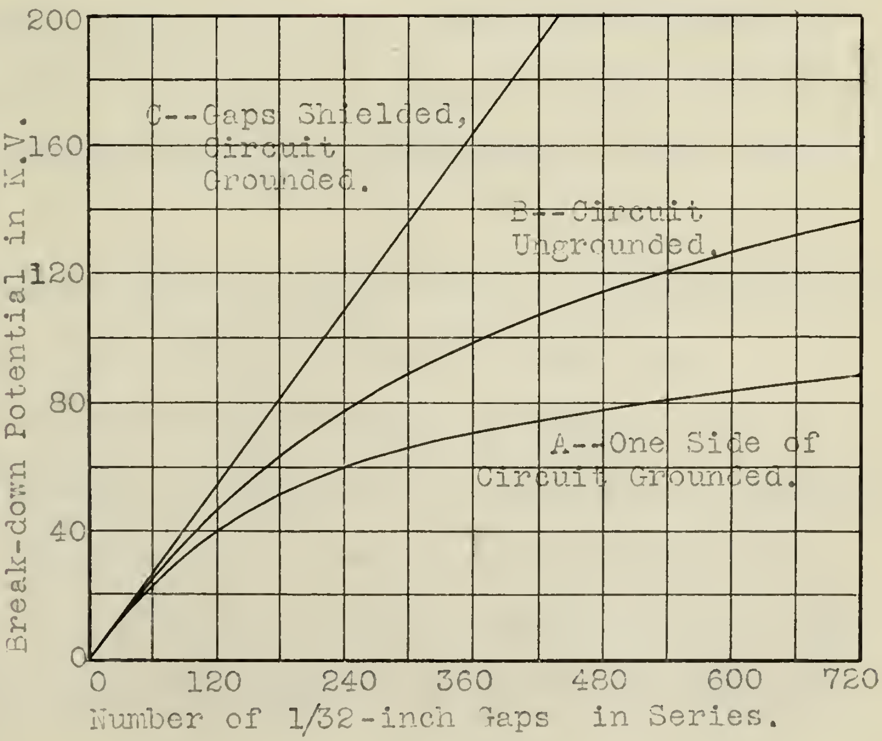


Fig. 3.9

curve A'. This curve seems to approach the ideal conditions more than any other. If in this case, the percent of shielded gaps and the break-down potential of the arrester are plotted as shown in Fig. 37, it is found that the maximum break-down voltage occurs when the shield covers about 25 per cent of the cylinders.

In all these cases only shields equidistant from the cylinders have been considered. But, since shields have merely a capacity effect, the distance from these to the cylinders also changes the shape of the potential gradient curves. Shields were bent in such a shape (Fig. 38) as to give the theoretical straight line C (Fig. 36) but a fairly good approximation to the ideal conditions is obtained by shielding 25 per cent of the cylinders, which in practice is much simpler.

By studying Fig. 36, it is evident that grounding distorts the curves considerably. Fig. 39 shows the relation between number of gaps and break-down potential for three cases:

A-- Gaps unshielded and one side of circuit grounded.

B-- Gaps unshielded, and circuit ungrounded.

C-- Gaps shielded and circuit grounded.

The advantage of shielding the cylinders of multigap arresters is, therefore, of a great practical importance. Arresters such as the "Giles" and "Compression Chamber" make use of this important principle to improve their characteristics.

The "Shaw" lightning arrester may also be classified as multigap, although its principles of operation have certain similarity to those of the "Multipath" arrester to be described later.

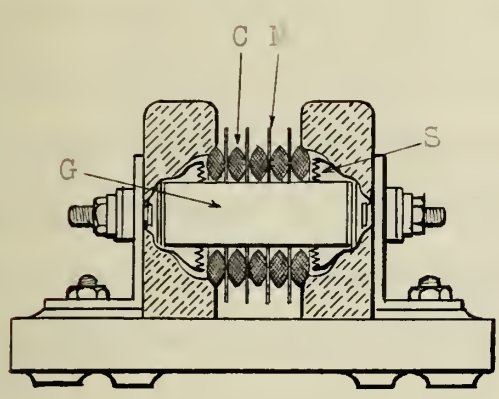


Fig. 40.-- The "Shaw" Type L Lightning Arrester.

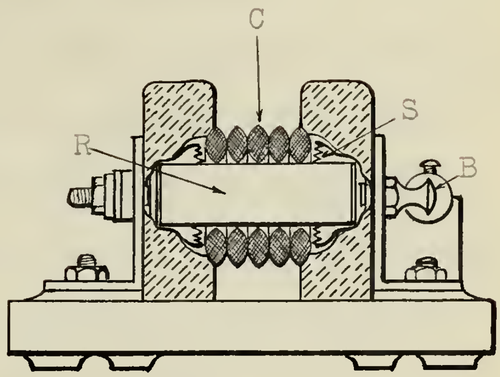


Fig. 41.-- The "Shaw" Type A Lightning Arrester.

There are two types of "Shaw" lightning arresters.

1.-- The construction in classes A, C and H is that of a series of condensers C, Fig. 41, mounted on a resistor arbor R made of a semiconducting material. The serrated brass pieces S form multigaps with the outer rings of the series. An adjustable additional gap B is put in series with the arrester proper.

2.-- Classes L and W differ from those already described in several respects: The same composition rings C, Fig. 40, are mounted on a glass arbor G and separated from each other by mica washers M. The serrated brass pieces S

form multigaps with the outer rings and are directly connected to the line and to ground respectively.

When the line becomes statically charged and the disturbance reaches the arrester, the charge is conveyed from the first ring to the next in the case of type A, or it is induced from ring to ring, in the case of type L arrester until all rings assume such a potential as to cause sufficient ionization in the multigaps at the ends that a discharge takes place. This discharge will be followed immediately by the dynamic current but the subdivision of the arc into many minute ones through the rings, will suppress the flow of this current.

In the first type, classes A and C are suited for voltages from 60 to 2,500 volts either direct or alternating current; class H, from 3,000 to 66,000 volts either direct or alternating current. In the second type, class L is suited for circuits of 60 to 2,500 volts direct or alternating current and class W are special arresters ranging up to 100,000 volts.

One of the most important protective apparatus based on the spark gap is the "Horn" lightning arrester. This arrester consists simply of a spark gap between two electrodes of special shape as shown in Fig. 54. There are several shapes of horn arrester electrodes: straight, as shown in Fig. 54, with sharp bends, (Figs. 42 and 62) and curved, (Figs. 45 and 46). One of the horns is usually connected to the line and the other to ground either with or without series resistance.

The operation of the horn arrester is as follows: When the potential of the line exceeds the disruptive value of the

shortest gap between the electrodes, an arc is there established. The ionized air in and about the arc is raised to a temperature so high that its density is very small compared with that of air at normal temperature. This difference in density causes the arc to rise to the upper ends of the horns increasing its length considerably. Such operation increases the resistance of the arc and consequently reduces its current until it ruptures. If the angle formed between the horns is too small, the arc cannot be elongated sufficiently to cause its own extinction, and if the angle is too large, the arc flashes back to the shortest gap and travels simply back and forth until the circuit is opened at some other place. Consequently, the angle should be made such as to avoid these two extremes. Angles between 60 and 80 degrees are the most commonly used.

The tendency of the arc to flash back depends to a certain extent on the intensity of the discharge. It is therefore advisable to keep the angle between the electrodes, near the shortest gap, relatively small and to increase it gradually toward the ends of the horns.

The history of the horn arrester may be said to date from March 4, 1896, when the Italian Government issued to E. G. P. Oelschlager and K. O. I. Schrottke a patent assigned to Siemens and Halske Electric Co. of Germany. The original idea was to have the horns as shown in Fig. 42, made up of straight portions of heavy copper wire with sharp bends and supported rigidly to porcelain insulators of ample capacity.

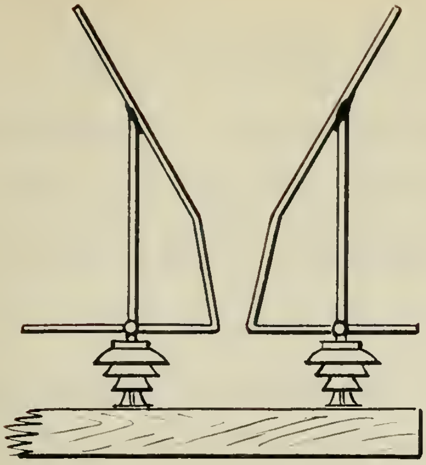


Fig. 42.- Siemens Horn Arrester.

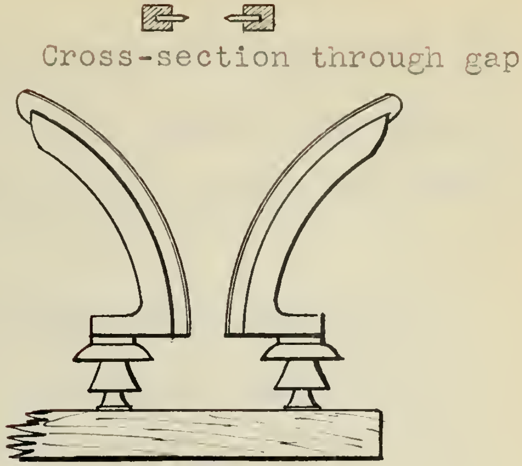


Fig. 43.- Iron Sheath Horn Arrester.

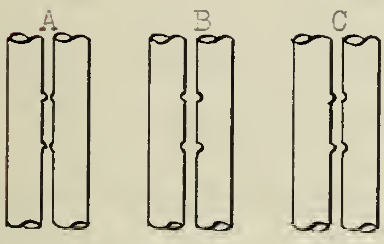


Fig. 44.- Effects of Arcs on
A.- Metal Electrodes,
B.- Carbon Electrodes,
C.--Metal and Carbon Electrodes, Respectively.

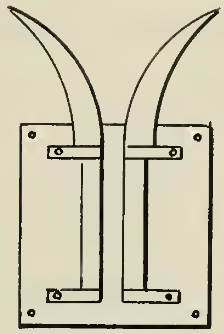


Fig. 45.- Balanced Gap Horn Arrester.

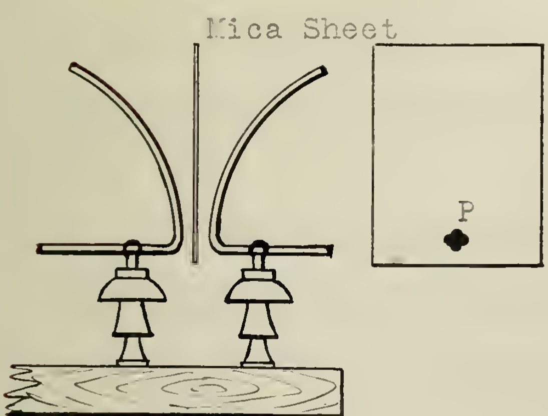


Fig. 46.- Mica Sheet Horn Arrester.

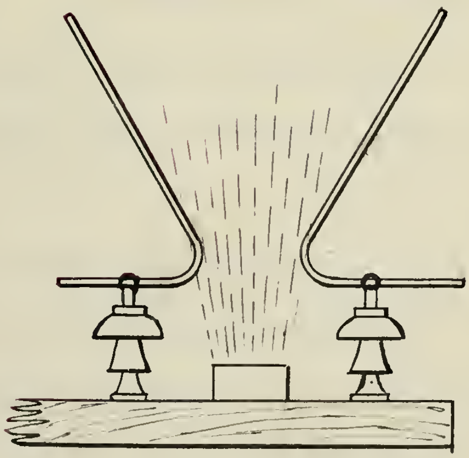


Fig. 47.- Radio-Active Substance Horn Arrester.

Horn arresters, as used to-day, have not improved much over those of the original patent. It is interesting to know the different methods used by inventors to increase the efficiency of this type of arrester.

Fig. 43 shows the arrester fitted with additional iron sheaths in order to increase the magnetic field within the gap and consequently drive the arc to extinction in less time than required by the common horn gap. As discussed in Chapter II, the great majority of disturbances due to atmospheric phenomena consist of high voltage and high frequency oscillations and the magnetic properties of iron under such conditions entirely disappear.

The formation of beads in the gap, during heavy discharges, slightly changes the rating of the gap. Another inventor thought of a scheme to avoid such a change. His theory was this: Metal gaps are deformed by discharges as shown in A, Fig. 44; with carbon electrodes the deformation is as shown in B; Consequently, a combination of a metal and a carbon electrodes will always keep the gap constant; and he devised the so-called "Balanced" horn arrester, shown in Fig. 45.

Still another inventor thought of shortening the time of rupturing the arc by means of the following scheme: A sheet of mica, Fig. 46, is placed between the horns of the arrester so that the perforation P on the mica is at the smallest gap. The inventor claims that the arc, after passing through the perforation, will be raised by the heating of the

air and flap over the sheet of mica, (without breaking or puncturing the mica); once there the arc will extinguish itself on account of its great length.

The use of radio-active substances to ionize the gap has also been tried. Fig. 47 represents the application of this scheme to a horn arrester. Such a gap is easily broken-down but the arc holds longer than in the standard gap.

A review of the above facts indicate that there are two principal defects in the horn gap:

1.-- When the gap discharges the static current, the dynamic current follows and persists until the length of the arc is sufficient to cause rupture, holding, therefore, a short circuit on the system for long intervals of time. The remedy for this trouble has been to insert enough resistance in the discharge circuit to limit this current and avoid serious disturbances. But the introduction of this resistance often limits the discharge caused by the overpotential on the line, which is a decided disadvantage.

The increase of magnetic field through the gap would obviously force the arc out more quickly. The arrangement shown in Fig. 48, involves the principle of increasing the magnetic field through the gap. The loop formed by the line wire causes the magnetic field through the gap. The shape of the bends of the line wire is of a particular interest. All bends are rounded but those of the gap; consequently, a high frequency wave has a greater tendency to discharge at the gap than at any other of the bends. It is claimed that

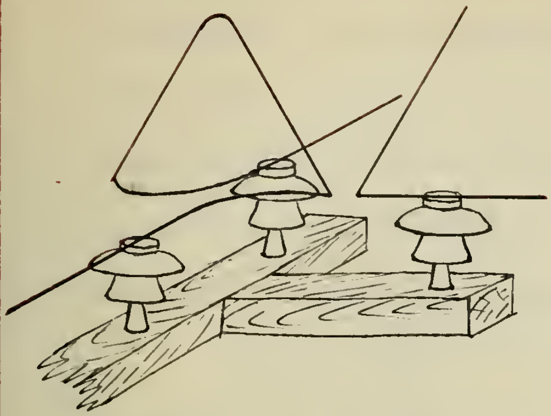


Fig. 48.-- Series
Horn Arrester.

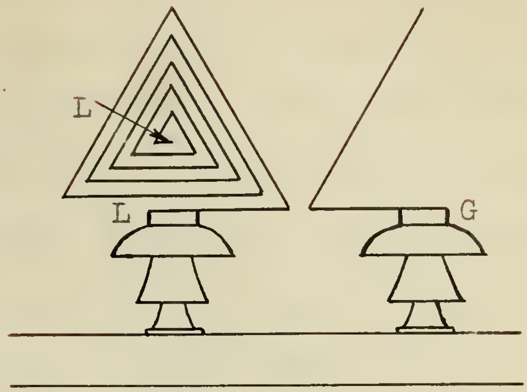


Fig. 49.-- Triangular Coil
Series Horn Arrester.

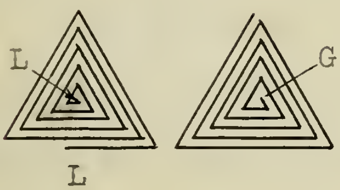


Fig. 50.

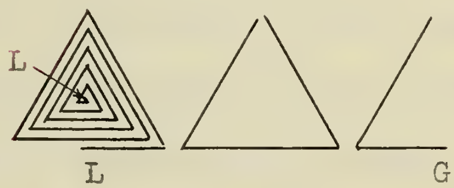


Fig. 51.

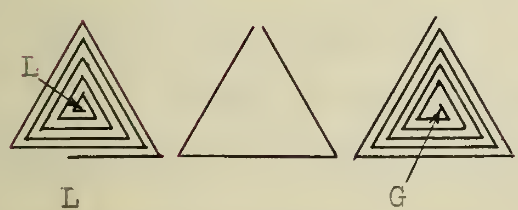


Fig. 52.

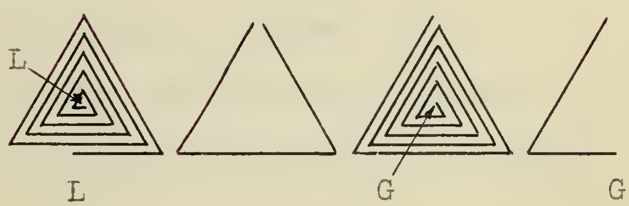


Fig. 53.

Note: In Figs. 49 to 53 inclusive, L denotes a connection to the line and G a connection to ground, with or without series resistance.

with this construction the accurate setting of the gap is no longer of prime importance, as an arrester thus fitted can have a gap 50 per cent greater and still be more sensitive than the old type arrester. The arc rises so quickly that no series resistance has been found necessary. This arrester can be used on circuits as low as 2,200 volts very effectively.

Fig. 49 shows an improvement on the previous type of arrester by increasing the magnetic field and the reactance or choke coil effect by means of the increased number of turns in the series coil. This arrester is adaptable to circuits as high as 45,000 volts, not needing any series resistance.

Fig. 50 shows still further development of the same principles. In this case, an additional reactance is carried by the ground lead. This, at first, appears to be a bad arrangement, since it is generally bad practice to place choke coils in the ground lead. Nevertheless, it is claimed that this form of arrester is very effective. The capacity effect of coils of such a shape may counteract their inductive effect. This point is, however, open to discussion.

Figs. 51 and 52 show still further development of this type of arrester. These arresters are used on circuits as high as 88,000 volts. The arc is divided into two parts in order to cause the lengthening in less time. It is claimed that this type of gap extinguishes the arc in 30 per cent of the time required by an old type horn.

Fig. 53 illustrates the final development of this type of arrester. For severe high frequency discharges, the

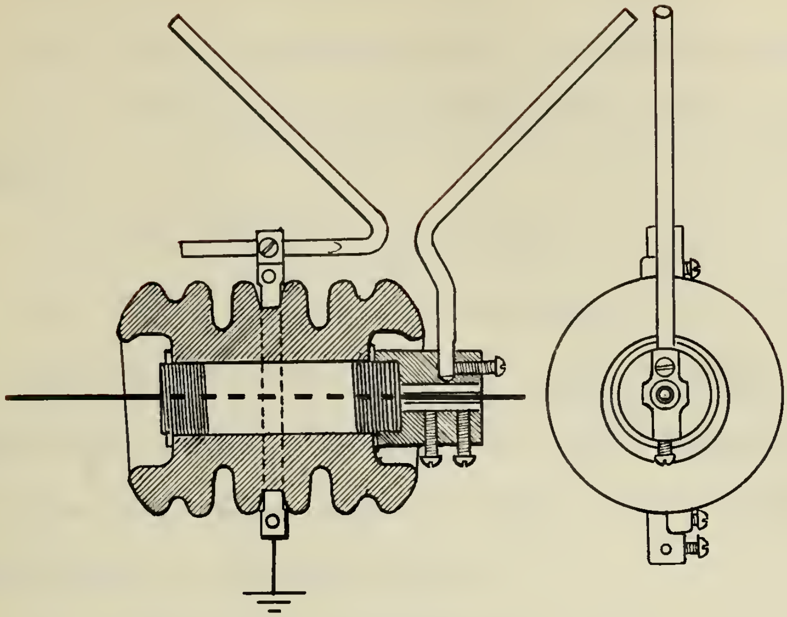


Fig. 54.-- "Universal" Horn Arrester.

third gap breaks, thus allowing maximum discharge.

These types of arresters were developed about 1910 and, so far, have given very satisfactory results.

Other less direct methods have been tried, for arresters placed along the line, to drive the arc to extinction sufficiently quick to avoid serious disturbances in the line.

The "Universal" horn arrester shown in Fig. 54 consists simply of a horn gap placed as near to the line conductor as practicable in order to utilize its magnetic field to drive the arc up more rapidly.

Blow-out coils are sometimes employed to drive the arc to extinction in horn arresters. There are five principal methods of connecting the blow-out coils on horn gap arresters:

1.-- Coil in series with the line.

2.-- Coil in series with the ground conductor.

3.-- Coil shunted across resistance in the ground conductor.

4.-- Coil shunting horn gap.

5.-- Coil separately excited.

The series horn arrester shown in Fig. 48 and the improved horn arresters Figs. 49 and 51 belong to the first class. The arresters shown in Figs. 50, 52 and 53 represent combinations of classes 1 and 2.

The second class seems to be the most objectionable because the coil impedes the high frequency discharges that must pass through it while the dynamic current flows with less difficulty. It may be that by giving the coils particular shapes, they may act as condensers and absorb high frequency discharges readily, but this behavior is still questionable.

Fig. 55 represents a horn arrester in which the blow-out coil is shunted across the resistance in the ground conductor. This resistance is made higher than that of the coil, so that the dynamic current passes mostly through the coil, while the high frequency discharge chooses the resistance.

Fig. 56 represents a horn arrester of the fourth class, in which the magnetic field across the gap is maintained continually by a coil connected from line to ground. This scheme is very seldom used at the present time but a modification of it is giving satisfaction. This modification consists (Fig. 57) of having one side of the coil connected

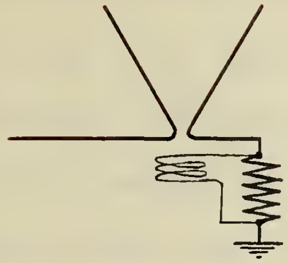


Fig. 55.- Blow-out Coil Across Resistance.

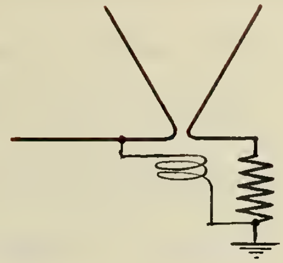


Fig. 56.- Blow-out Coil from Line to Ground.

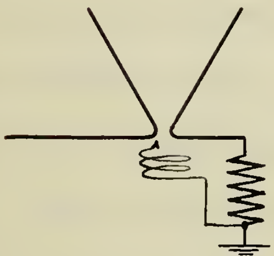


Fig. 57.- Blow-out Coil from Line, through Gap to Ground.

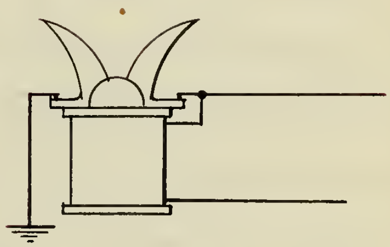


Fig. 58.- Magnetic Blow-out Horn Arrester.

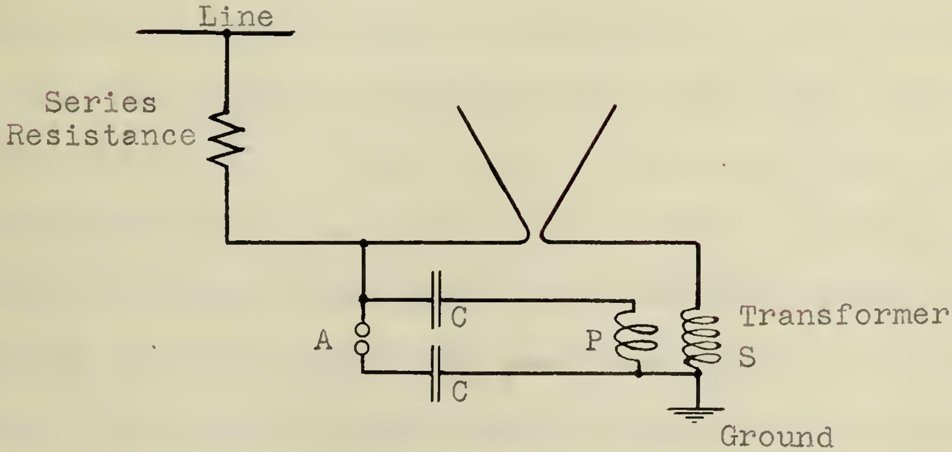


Fig. 59.-- Lightning Arrester Relay Applied to a Horn Gap.

to ground and the other forming a small gap with the line horn directly under the main gap. This small gap is set very close to the line potential, so that in case of a wave reaching the arreater, this gap is the first one to break. The main gap is thus ionized and easily broken down by the abnormal potential of the wave. Then the dynamic current follows but the action of the coil forces the arc to extinction. This principle of starting the arc by means of an additional gap was first tried with a non-inductive resistance in series, instead of a coil.

Fig. 58 represents an arrester of the fifth class. In this arrester the blow-out coil is made very powerful, and consequently, the length of the horns has been correspondingly reduced. The blow-out coil is excited from the generator and kept that way all the time. This type of arrester is not fitted for very high voltages.

Lightning arrester relays have also been tried to help the horns extinguish the arc. Fig. 59 is a diagram of the connections of such a relay. Its operation is as follows: When the line reaches the maximum safe potential, gap A, which is very closely set, breaks and the main gap follows immediately. The oscillations set up by the spark in gap A, excite then the high potential transformer whose secondary raises the potential of the grounded horn and thus helps to extinguish the arc. The scheme is satisfactory and works on circuits as high as 6,000 volts, alternating current.

The improper setting of horn gaps has been the cause

of considerable trouble. Mr. C. C. Garrard# has conducted an extensive series of experiments on this subject, resulting in the derivation of the following formula,

$$V = S\left\{4.605\cdot r\sqrt{\frac{a}{a+4r}}\ \log\left[\frac{\sqrt{a^2+4ar}+a}{\sqrt{a^2+4ar}-a}\right]\right\}$$

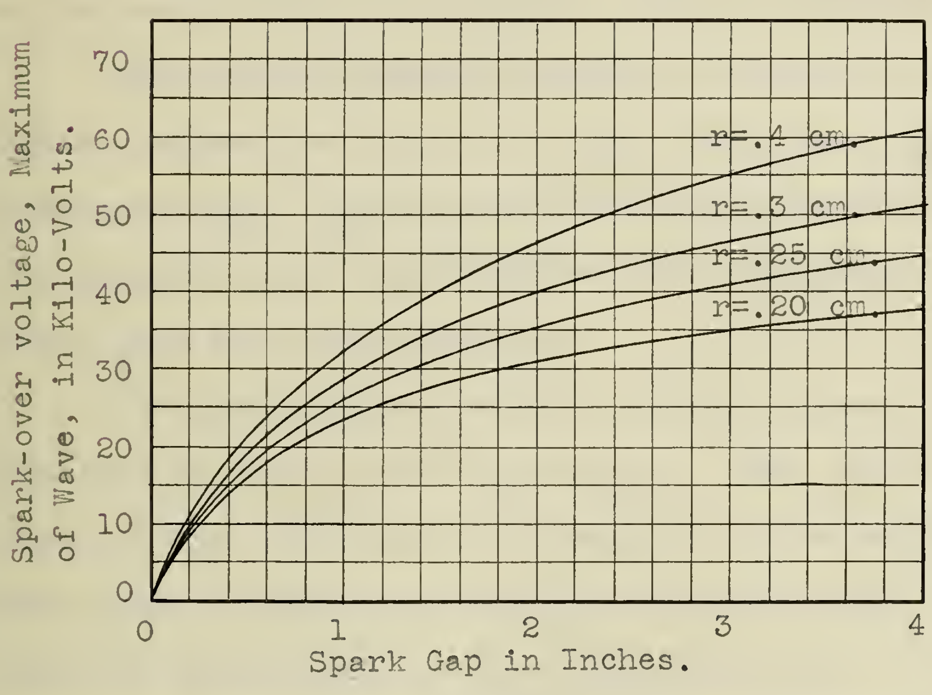


Fig. 60.

in which:

V = Maximum value of voltage wave.

S = Disruptive voltage of air per centimeter, (=2,500).

r = Radius of wire in centimeters.

a = Minimum distance between wires in centimeters.

#-- Horn Lightning Arresters.- Elec'n. Lond. Mar.20,1914

Values from this equation are plotted in Fig. 60. It should be remembered, however, that the values given in the curves are maximum voltages of the waves, thus, they must be multiplied by the factor .707 to obtain the effective values of voltage, assuming of course that the waves are sinusoidal. These curves can be used as a rough approximation, since the break down voltage depends on the altitude and on the character of surface of the conductors forming the gap, as discussed under electrostatic corona in Chapter II.

The excess pressure generally allowed in transmission systems ranges from 25 to 50 per cent; the higher the working voltage, the smaller the allowable excess. This should also be taken into consideration when determining the dimensions of the gaps for horn arresters.

The behavior and relative merits of horn lightning arresters are still under discussion. Many claim that horn arresters are absolutely indispensable on transmission systems, while others claim that this type of arrester is simply a source of disturbance in power transmissions. The general opinion is that horn arresters have not any great value when used in their simplest form for protecting power circuits. Horn arresters should be used as emergency or auxiliary devices rather than as normal protective apparatus. If the horn is connected to the line without any resistance in series, the arc will short-circuit the system for considerable lapses of time. If it is connected to a resistance high enough to avoid serious disturbances, its protective value is correspondingly

decreased. When a horn arrester discharges to ground, with no resistance in series, all synchronous machines will be thrown out of step producing very serious disturbances. If a fuse is used in the discharge path, the combination can offer protection against over pressures only as long as the fuse is not blown out, which results in lack of protection during storms, when fuses cannot be replaced. However, several fuses may be connected to the horn, so that when one is blown out another can be inserted by means of a switch. But this arrangement makes the fuses and not the horn the actual protective device. The breaking of the short circuit formed by a horn arrester will often cause more damages than the original disturbances. Under certain conditions (see Chapter II) the breaking of the arc is apt to cause very high potential strains so that the horn may become the cause instead of the protector from disturbances.

In view of all these difficulties, designers have struggled to devise an arrester which would give satisfactory operation under any circumstances.

There has been recently put on the market# a type of horn arrester as shown in Fig. 61 which consists essentially of a horn gap and a number of resistance units so arranged that as the arc rises in the gap, resistance is automatically cut into the circuit. Thus, without any moving parts, the current is rapidly cut down so that it breaks easily, without

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#--By Schweizer and Conrad.

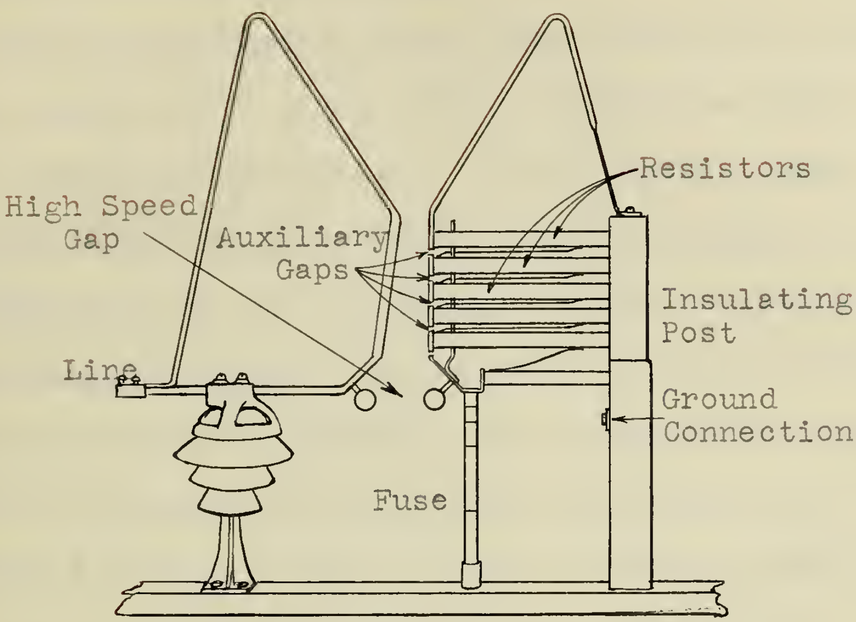

Fig. 61.-- Graded Resistance Horn
Arrester.

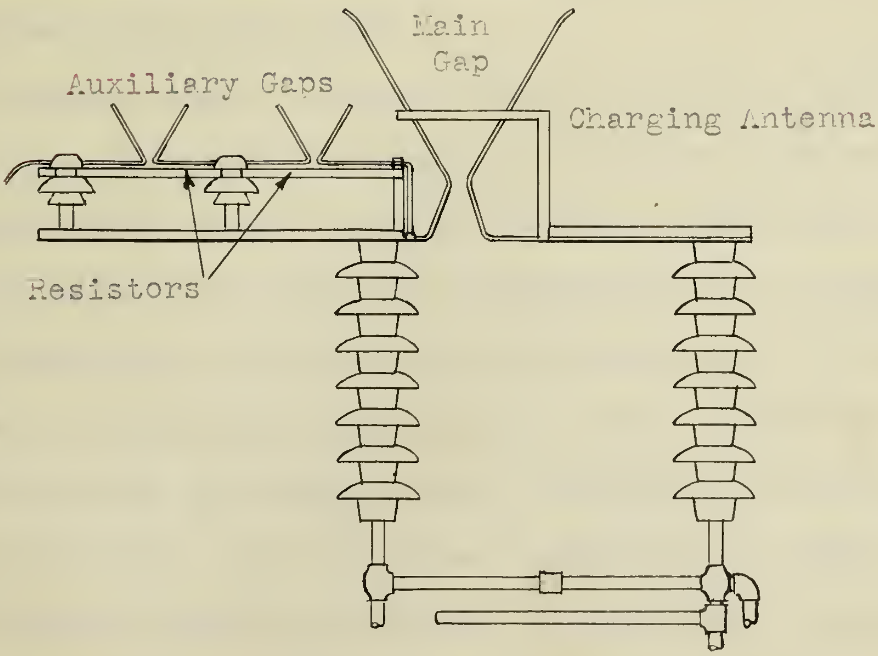

Fig. 62.-- Selective Resistance Horn
Arrester.

disturbing the line. A sphere gap is provided to assist the dissipation of high frequency waves that may come into the system from some external source.

When the potential of the line passes the allowable maximum, the arc will start across the smallest gap which has all the resistance in series. If the potential rise is of low energy capacity, the current flowing through the gap and total resistance may be sufficient to keep the voltage down to approximately normal. If the current flowing through the gap and resistance is insufficient to keep the voltage down, the arc will break across the next lower step and a larger current will flow. If this current is still insufficient to keep the voltage down to a safe value, then the next lower step will arc across, etc., until the no-resistance gap is reached when the system will be actually short-circuited and practically unlimited current can flow.

When the step is reached where the flow of current is sufficient to dissipate the energy of the wave, the voltage is reduced to its normal value and the arc rises along the converging part of the horn and consequently, the dynamic current is reduced by the increasing resistance and the strength of the arc is correspondingly reduced, and consequently, it has no difficulty in rising on the diverging horns and causing its own extinction. The arc is so weak when it breaks that the disturbance created on system is practically negligible. This type of arrester is used on systems as high as 44,000 volts.

The "Selective Resistance" horn arrester shown in

Fig. 62 accomplishes the same result as the graded resistance arrester, by placing resistors in series with the main gap and shunted by small horn gaps. When a disturbance reaches the arrester, the main gap is the first one to break. Such a discharge is limited by the series resistances and may not be sufficient to keep the line voltage to a safe value. If such is the case, the auxiliary gaps break, and then, the discharge is only limited by the impedance of the grounding circuit. The current is then diminished by the rising of the arcs and finally by the breaking of those in the auxiliary gaps, so that the breaking of the main gap seldom produces serious disturbances in the line.

This type of arrester is especially adaptable to use in conjunction with aluminum cell arresters for high voltage circuits. In such cases, the series resistance is used for charging the cells without causing appreciable disturbances in the system.

The uses of the horn arrester may be classified as follows:

1.-- For protection of insulators along transmission lines, horn arresters are installed along the line with gaps adjusted to break down at a potential lower than the wet flash-over potential of the insulators. Resistance to ground is sometimes used with these arresters, but in all events, the system will be disturbed by the breaking of the short-circuiting arc; the only difference is that with the horn, the trouble is of short duration and prevents damaging the line insulation,

but without it, the insulation may be so damaged that the line has to be disconnected for repairs. This difference is not insignificant, especially in systems where the continuity of service is of prime consideration. With local, stationary phenomena of high frequency, the use of horn lightning aresters along the line is advisable. The reliability of operation of horn arresters depends, in many instances, on the design of the horns and gap.

2.-- The most general use of this type of arresters is as auxiliary to other types having better characteristics. The combination of multigap and horn arresters has proved rather satisfactory. The horn arresters can take care of low frequency oscillations and surges, while the multigap is better adapted for discharges of high frequency. Electrolytic lightning arresters, when used in alternating current circuits, require, at least, one additional gap in the discharging circuit. In high potential circuits, the aluminum cell arresters should be charged through a resistance in order to avoid disturbing all paralleling lines and particularly those of weak current systems as well as the line itself. Fig. 63 shows the essential features of an aluminum arrester protective circuit. The main gap is placed directly under the charging gap and its horns are relatively short, so that, if a heavy discharge occurs, the main gap breaks and the arc, in rising, is transferred to the charging gap where it finally breaks. The charging gap can take care of light discharges very effectively. This gap is made easily adjustable so that

the operator can safely charge the arresters whenever necessary. Where horn gaps of the design shown in Fig. 62 are employed,

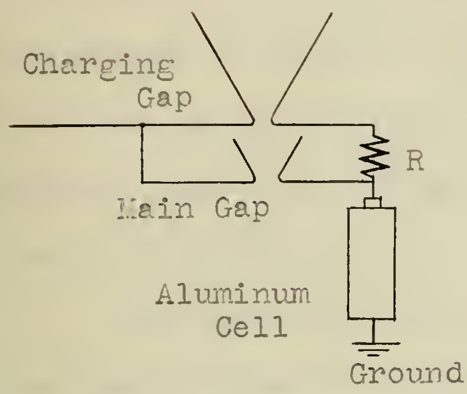

Fig. 63.- Essential Features of an Aluminum Lightning Arrester Circuit.

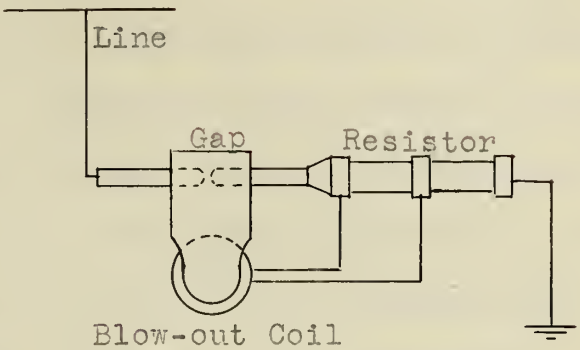

Fig. 64.- Diagram of Connections of a Magnetic Blow-out Lightning Arrester.

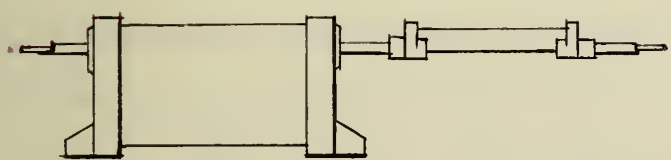

Fig. 65.- Permanent Field Magnetic Blow-out Lightning Arrester.

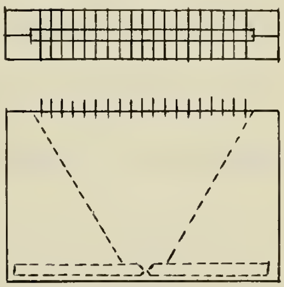

Fig. 66.- Details of Arc Chute and Grid for Magnetic Blow-Out Lightning Arrester.

the grounded horn of the main gap is fitted with an additional antenna and can be rotated about the axis of the insulator and thus start the charging arc in the gap.

The arrester shown in Fig. 58 gives rise to another type of protective apparatus by replacing the horn shape gap by other shapes and changing the arrangement of its essential parts.

Fig. 64 shows a typical arrangement of a "Magnetic Blow-out" arrester. It consists simply of a carbon or metal gap placed in the magnetic field of a coil shunted to a resistance in the discharge circuit. The high frequency discharges flow through the resistance and gap but the dynamic current chooses invariably the path through the coil and consequently creates a magnetic field that blows the arc out of the gap.

The arc extinction principle in this arrester was developed similarly to that applied to horn arresters.

The original magnetic blow-out type of arrester was invented by Prof. Elihu Thomson. The design in present use was put in an efficient form by Mr. E. M. Hewlett and so long as the application was limited to 600-volt circuits, no improvement was found desirable. The increases in trolley potentials to 1200, 1800 and 2400 volts direct current, however, taxed the arc extinguishing device of a single arrester beyond its limit and it was necessary either to place two or more arresters in series or reconsider the elements for a new design.

There are certain elements fundamental to the arrester which are inherent in the new design. These essential elements are: A gap in a magnetic field perpendicular to it; a slight amount of series resistance, especially where a battery is used on the circuit, to limit the dynamic current to a value less than a short circuit when a discharge takes place across the gap; and an arc chute to direct and help extinguish the arc.

In the older designs the magnetic field was produced by means of an electromagnet shunted across part of the series resistance as shown in Fig. 64. When this arrester failed to extinguish the dynamic arc it was usually due to the loss of the magnetic field. The insulation of the coil of the electromagnet had necessarily a limit and when the lightning discharge produced a drop of potential across the coil beyond this limit, the coil was shunted out by a spark. With no magnetic field to cause the arc to rise, it remained in the gap and the current continued to pass through the arrester until the energy loss in the resistance overheated it and a short circuit resulted. In practice such failures are relatively infrequent.

In place of an electromagnet is a permanent magnet in the new design. Long pole pieces are placed on the magnet to give a better directed and concentrated field in the path of the arc.

The arc is made to play into the loop formed by the steel of the magnet and thus gives the maximum remagnetizing effect at every discharge.

For the protection of 600-volt circuits it is desirable to have the spark potential of the gap as little above 600 volts as practicable. In the older form of arrester it was found undesirable to reduce the gap to much less than .025 on an inch. The minimum value of gap setting was determined mostly by the tendency to splash molten metal from the crater of the arc across the gap and thus permanently short-circuit it.

The magnetic field around the gap was not strong enough to lift a molten metal bridge out of the gap. There is another factor in the older design that magnified this effect and, furthermore, made it more difficult to pull the arc out of the gap into the arc chute. This factor consisted in the formation of an arc crater on the electrodes before the magnetic field appeared in the gap. The magnetic field coming from an electromagnet is dependent on the establishment of a current through the coil. The time constant of the coil delays for a brief moment the appearance of the magnetic flux. The formation of the molten crater on the tips of the electrodes has two effects. First, it wears away the points of the electrodes and varies the gap length; and second, it requires more magnetic force to move an arc that terminates in a stable molten crater. When a permanent magnet is used, the magnetic field is always present. The arc begins to move as soon as it appears, leaving no time for the formation of a definite crater. With this new condition it is immediately practicable to effect two important changes in the design of the arrester: the mass of metal in the electrodes can be reduced and the electrodes, no longer subject to wear at the gaps, can be fixed once for all with a definite minimum gap setting between them. Furthermore, in the absence of a molten crater, it is permissible to reduce the gap setting to nearly half the previous limit.

If the arc chute is made high enough the arc may be extinguished in the chute. But for use with potentials above

1000 V. it becomes of unpractical dimensions. Therefore, another device is added to aid the complete extinction of the arc. It consists of many metal plates laid on their edges at the top of the arc chute, and perpendicular to the chute. These metal plates are insulated from each other and spaced a fraction of an inch apart. (Fig.66.) When the arc rises out of the chute it is broken up into as many parts as there are spaces between the plates of the grid. The grid becomes, in effect, a multiple gap arc extinguisher. In these gaps two effects are present. First, the arc is cooled by the contact with the cool metal of the grid; and second, each arc absorbs 45 volts or more at its electrodes. Forty-five volts is the minimum potential that can establish an arc, therefore, if there are fifteen plates in the grid, the arc cannot be established between the plates of the grid.

By using a grid consisting of sixteen plates or more in an arrester designed for 600 volts direct current, an arc will be entirely extinguished by the grid and will emerge in the form of heated but de-ionized gases. These gases are passed around to the bottom of the arc chute again; thus, it is no longer necessary to have the arc discharge into the open. The arrester is, consequently, enclosed and requires no containing box of wood.

The resistance rod is placed outside the arrester proper in order to facilitate its inspection and replacement.

Substances whose conductivity varies with the impressed voltage are often used as media for lightning protective

apparatus. These substances exist in the three states: solid, liquid and gaseous.

The first classification can be further subdivided into compact and pulverized solids.

Carborundum is the foremost representative of this kind of compact substances. Fig. 67 shows a very common arrangement for a type of protective devices known as "Multipath" lightning arresters. It consists essentially of a carborundum disc, of a section as shown in the figure, cast between two brass plates. The discharging disc consists of ground and gauged particles of carborundum held together by a binding compound. This compound is a good dielectric.

The action of this arrester is briefly as follows: When the potential difference between line and ground exceeds a certain specified maximum the minute internal gaps of the carborundum disc break down thus providing a free path for the high frequency charge; but the great subdivision of the spark impedes the formation of arcs by the dynamic current, since it takes at least 45 volts to maintain an arc, no matter how minute. This arrester, therefore, does not suppress the dynamic arc but impedes its formation, so that its operation cannot cause any dangerous after-effects.

For voltages up to 400, the carborundum disc is connected directly from line to ground but for voltages up to 750, a small gap is placed in series with the disc, as shown in Fig. 68. Both of these arresters discharge at lower rise above normal than is possible with any other form of arrester

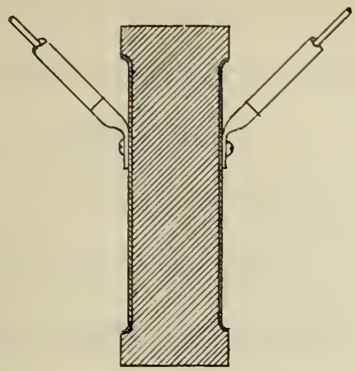

Fig. 67.- Multipath Lightning Arrester. (under 400 volts)

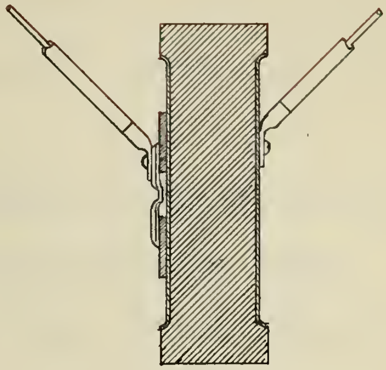

Fig. 68.- Multipath Lightning Arrester. (400 to 750 volts)

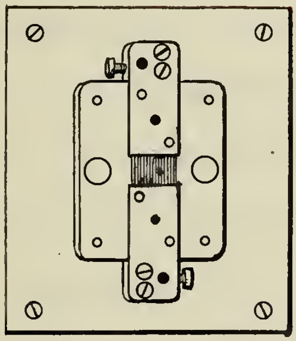

Fig. 69.- Charred Wood Lightning Arrester.

except the electrolytic and the condenser types to be described later.

The only impedance to a static discharge in a multigap arrester is the resistance of the arcs. This arrester has, therefore, the lowest equivalent gap and maximum discharge capacity of any, for similar service, except the condenser and electrolytic types.

Multipath lightning arresters are usually contained in cast iron boxes of relatively small size and weight, con-

venient, therefore, for handling and mounting. One half of the casting can be easily removed should inspection or repairs be necessary.

Fig. 69 shows the essential parts of a "Charred Wood" lightning arrester. It consists of two non-arcing metal electrodes mounted on a 'lignum vitae' block, flush with its surface and at a certain distance from each other. The surface of the wood between the electrodes is grooved and charred forming a high resistance connection at normal voltages, but a free path for disturbances of excessive voltages. Other grooves at right angles to the discharge path provide a vent for the discharge gases. A second block, fitting closely over this mounting block, so confines the gases produced by the discharge that they develop a very high pressure which expels them violently through the grooves. As the vent grooves are at right angles to the discharge path, the expulsion of the gases almost instantly ruptures the arc. On account of this particular feature of the arrester, no series resistance has been found necessary in connection with it.

The Charred Wood arrester can be used in either direct or alternating current circuits. Single units can protect circuits up to 2,000 volts and as high as 10,000 volts by using four units in series.

The "Anderson" self cleaning lightning arrester for telephone protection may also be classified as multipath although it contains two air gaps. Fig. 70 shows the essential parts of this arrester. The carbons C C and the magnet coil

M are connected in series with the line. Carbon D is rigidly attached to the magnet armature and is pivoted at the other end and grounded. Consequently, whenever the line operates carbon D is vibrated and the dust and carbon particles, accumulated on its surface, are shaken off keeping the gaps in perfect working condition.

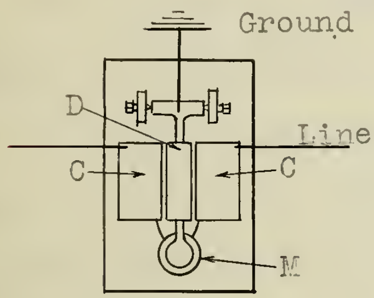

Fig. 70.- The "Anderson" Self-Cleaning Lightning Arrester.

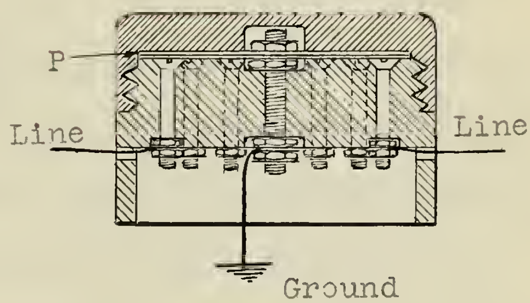

Fig. 71.- The "Cox" Multiple Lightning Arrester.

The "Cox" multiple lightning arrester shown in Fig. 71 consists simply of a grounded plate P separated by a thin perforated mica disc from the heads of 10 brass screws mounted on a porcelain frame. Each one of the screws is directly connected to a telephone wire so that one arrester can take care of as many as ten lines. The protection is afforded by a simple gap to the ground plate.

Some pulverized conductors have the property of coher-

ing when subjected to electrical strains. If such powders are put into non-conducting tubes and these placed in series with low potential circuits, it will be found that their specific resistance is high and decreases as the impressed voltage increases. This property was first discovered by Barnly about 1900 and has had very important applications. Receiving apparatus in wireless telegraphy were first developed on this principle. Some lightning protective apparatus have also been designed on this principle.

The "Line Discharger", shown in Fig. 72, consists essentially of a small air gap in series with several glass tubes filled with oxidized metallic particles. The discharger is connected directly between line and ground and its function is to free the line not necessarily from overpotentials but from minor high frequency disturbances produced by the accumulation of static and similar causes. Line-to-line disturbances are often taken care of by this type of discharger.

Non-arcing metal cylinders are also used for discharging accumulated static on power lines.

The "Loose Coherer" arrester shown in Fig. 73, consists essentially of two porcelain tubes filled with certain pulverized conductor and placed in series with a metal spark gap. Sometimes a fuse is used in the grounding circuit. The action of the coherer is such as to present a free path to discharges of abnormal frequency and potential and to impede the formation of the arc. This property is due to the multipath effect of the conducting particles within the tubes. When coherer

arresters are used without a gap in series, they cause a continuous drain on the system and when used on direct current

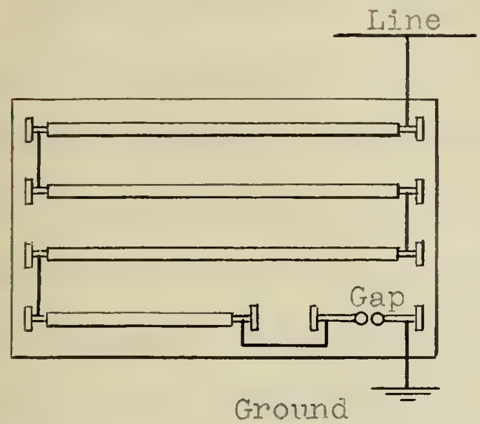

Fig. 72.- The "Line Discharger".

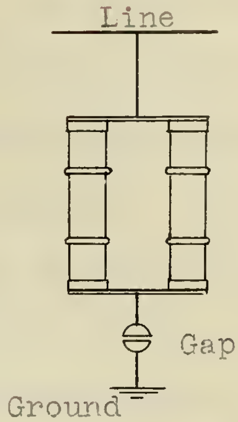

Fig. 73.- "Loose Coherer" Lightning Arrester.

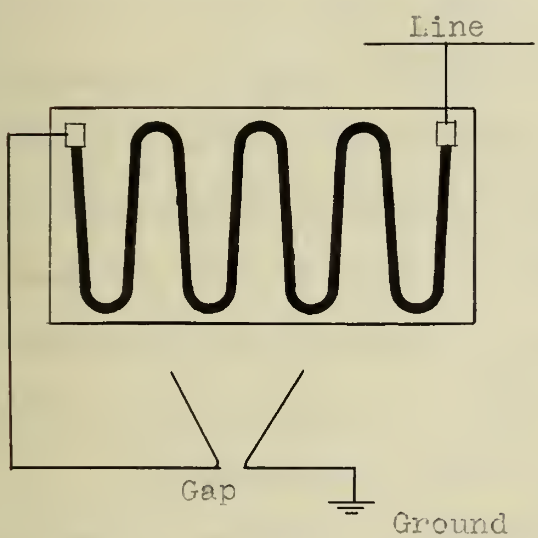

Fig. 74.- "Surge Discharger".

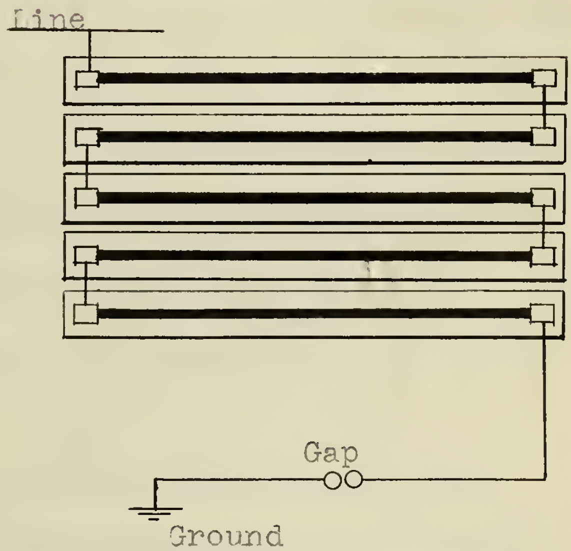

Fig. 75.-"High Frequency Discharger".

circuits they are liable to become polarized and thus increase the losses and reduce the protective value. The series gap obviates these troubles and is therefore to be recommended.

The properties of carbonized Brazil wood in the pulverized form were briefly discussed in Chapter III. Such

a powder has not only the coherer characteristics but also a large negative temperature coefficient. Fig. 74 shows an earthen plate in which a zig-zag groove is cut and the space is filled with Brazil wood carbon powder; one end of the carbon is connected to the line and the other to a horn gap leading to ground. This arrangement constitutes what is known as the Pulverized Carbon Surge Discharger. When the surge wave reaches the protector, it finds an easy path through it to ground. The discharge is proportional to the conductivity of the protector but the rise in temperature in the latter simultaneously decreases its resistance and hastens the flow of the surge current until the potential of the wave decreases to a safe value and then the dynamic arc is extinguished causing comparatively small disturbance in the system. The same medium is used to discharge high frequency oscillations but in this case the carbon conductors have a very large resistance and sometimes a number of these is put in series with the sphere gap, as shown in Fig. 75.

To the second class, or liquid media protective apparatus, belongs the "Water Resistance Arrester" shown in Fig. 76. It consists of a galvanized iron tank containing three compartments so arranged that a small stream of water can flow from one that is connected to the water main to the other two and finally to a drainage pipe. Each compartment contains a block of carbon suspended in such a way as to form considerable gaps with the metal walls. The carbon blocks can be connected to the cross bars of the line choke

coils through suitable plugs. When the apparatus is connected to the line it can discharge any lightning disturbances that may reach the choke coils, but the leakage current through it is so large that it would be uneconomical to have it connected permanently to the line. The use of such a protective apparatus hardly deserves discussion, but it is brought forth

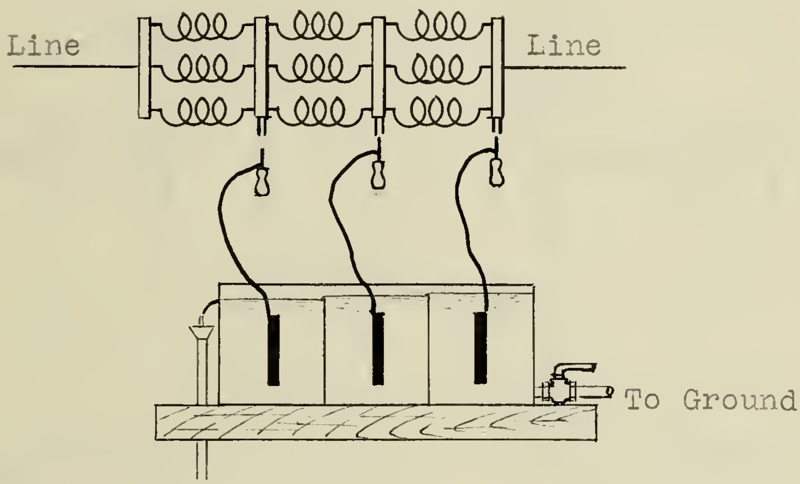

Fig. 76.- The "Water Resistance Arrester".

to show the problems which confronted the early designers and to contrast our present practice with that of one or two decades back.

Water columns and water jets are often used in Europe to free lines from accumulated charges. The resistance of water columns and jets of the dimensions used is considerably greater than that of the water in the tank previously described and the leakage currents through them are corresponding-

ly smaller. The "Water Column" Fig. 77 consists of two heavy glass tubes which carry the water from the water mains through the brass coupling B , to which the line is connected, and

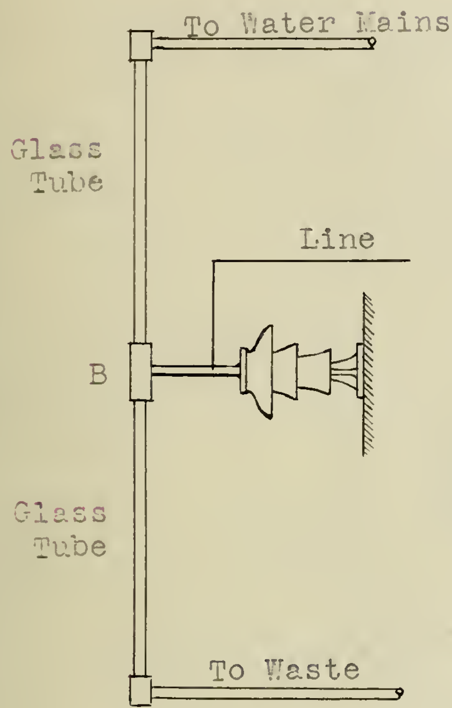

Fig. 77.- "Water Column Discharger".

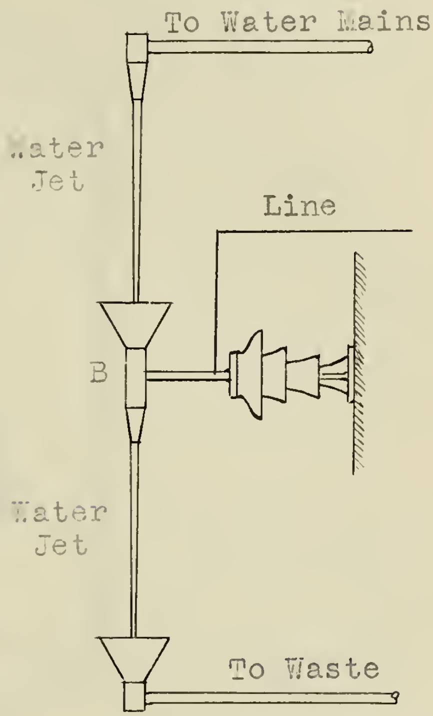

Fig. 78.- "Water Jet Discharger".

finally to the waste pipe, which, as well as the water main pipe should be thoroughly grounded. The "Water Jet" discharger shown in Fig. 78 is very similar to the water column. The main difference is that the water falls freely from the jets to the funnel shaped receptacles.

The high cost and the upkeep of these types of water resistance protective devices make their use prohibitive.

The "Garton Multi-Vapo-Gap" lightning arrester shown in Fig. 79, is a representative of multipath arresters using gaseous media. It consists simply of two metal electrodes,

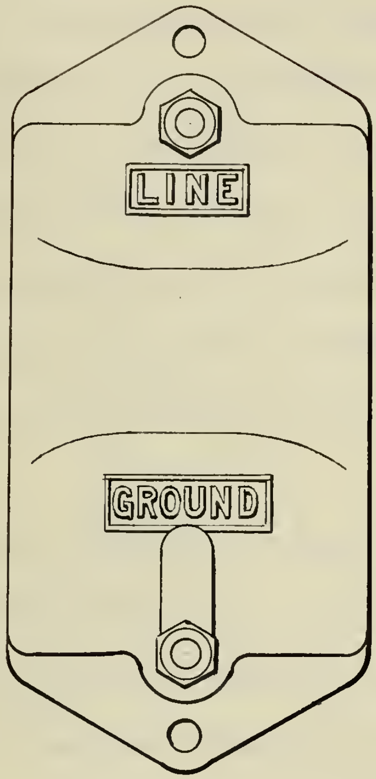

Fig. 79.- The "Multi-Vapo-Gap"
Lightning Arrester.

to which the line and ground connections are made, leading to a hermetic porcelain chamber containing the gaseous medium. This medium is a highly hygroscopic mass holding a fixed and definite amount of moisture in suspension which is maintained in a static conductor form of absolute uniformity. The nature of this static conductor is such that the

dynamic current cannot flow through it. The impedance of this arrester to lightning phenomena is virtually nil owing to the fact that the myriads of moisture globules, though mechanically separated due to the chemical hygroscopic composition, are infinitely close together. This is electrically proved by the so-called equivalent spark-gap test; these gaps are almost immeasurable. The hygroscopic composition of the body of this arrester prevents the flow of normal current as it is, of course, impossible to establish arcs between the water globules. In this arrester, the multiplicity of vapor gaps eliminates the necessity of having an air gap. This feature, together with the low impedance, makes the building up of static on the line impossible.

The mechanical features of this arrester are simply its electrical indestructiveness, and its compactness. The manufacturers claim that this arrester is absolutely weather proof. There is no question about its good mechanical features but it is doubtful that its electrical characteristics remain unaffected at low ambient temperatures, on account of the consequent condensation of the suspended moisture in the medium.

Rarified air is also used as a medium for protective apparatus working on low voltages and weak current systems where close adjustment is necessary.

The "Brach" telephone lightning arrester shown in Fig. 80 consists of a gap formed by two metal electrodes placed in a hermetic chamber containing rarified air. This type of

Fig. 80.- The "Brach" Telephone Lightning Arrester.

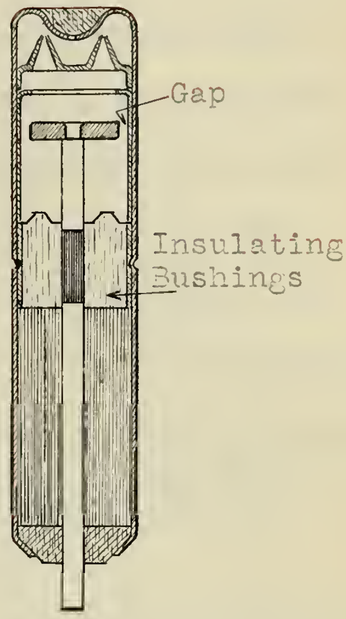

Fig. 81.- The "Vacuum Tube" Telephone Lightning Arrester.

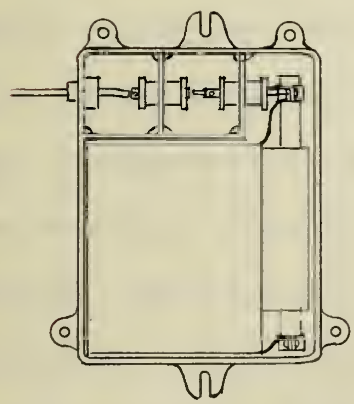

Fig. 82.- "Condenser Type" Lightning Arrester.

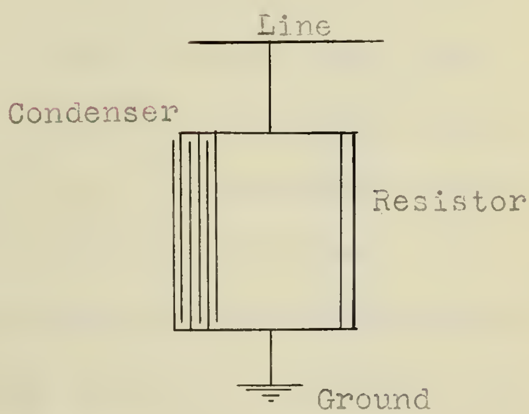

Fig. 83.- Diagram of Connections for the "Condenser Type" Arrester without Series Gap.

arrester is commonly used for line to line protection although sometimes it is used to discharge disturbances to ground.

The "Vacuum Tube" lightning arrester shown in detail in Fig. 81 consists of a partially exhausted chamber whose metallic wall forms one of the electrodes; a non-arcing metal disc supported by an insulated rod constitutes the other. The dimensions of the gap are such that relatively heavy discharges can pass through the arrester without affecting its sensitivness. This type of arrester is often used in multiple with non-arcing metal gaps so that in case of heavy discharges the arrester will not be destroyed. Fig. 23 shows such a combination as used for telephone protection.

Designers have been able to use the absorbing property of condensers to protect lines, especially direct current, against disturbances of abnormal frequency and pressure. There are two forms of this type of arrester. One consists of a condenser shunted by a high resistance and in series with an adjustable spark gap, as shown in Fig. 82; the other type consists simply of a condenser shunted by a high resistance as shown diagrammatically in Fig. 83. The condensers used on line mounting arresters have a capacity of about .3 microfarads, equivalent to the capacity of about 30 miles of average line. In the car mounting form, the condensers have a capacity of one microfarad, equivalent to that of 100 miles of average line. The main object of the resistance shunting the condenser is to keep it discharged to zero value which is not so essential for line protection. But such a resist-

ance causes a continuous leak where no series gap is used. These arresters are often directly connected from line to ground without any auxiliary apparatus.

The condenser freely discharges to ground the high frequency waves that may happen to travel along the line, but the direct generator current cannot follow. The resistance, where used, is not in the static discharge path; it can be therefore, of a very high value and still not interfere with

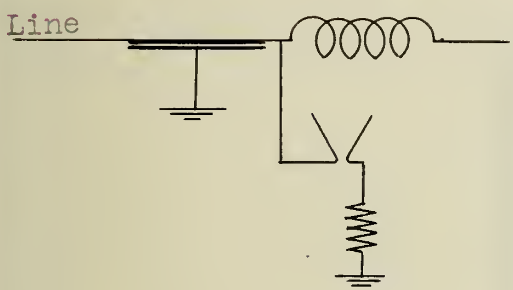

Fig. 84.- The "Zig" Lightning Arrester.

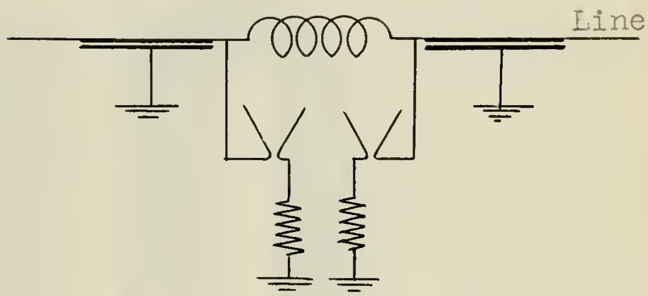

Fig. 85.- The "Zig" Lightning Arrester for Use along the Line.

the static discharges. Where the series gap is used, the full capacity of the condenser is always available but in the line arrester without gap or resistance, the condenser is charged up to line voltage but, having no gap, it is ready to discharge all static formed at any voltage. These types of arresters are suitable for direct current circuits up to 1,500 volts.

The "Zig" lightning arrester, Fig. 84, also uses a condenser from line to ground but followed by a reactance coil which leads to the transformers. A horn gap with series resistance is connected as shown in the figure. Its operation

is as follows: When a high frequency wave reaches the arrester, the condenser immediately operates, discharging at least part of the energy to ground; and the other part is impeded by the choke coil and forced through the horn gap to ground. Fig. 85 illustrates the arrangement when used along the line. This latter type acts as a barrier to traveling waves of any kind, and is particularly fitted for use on direct current circuits.

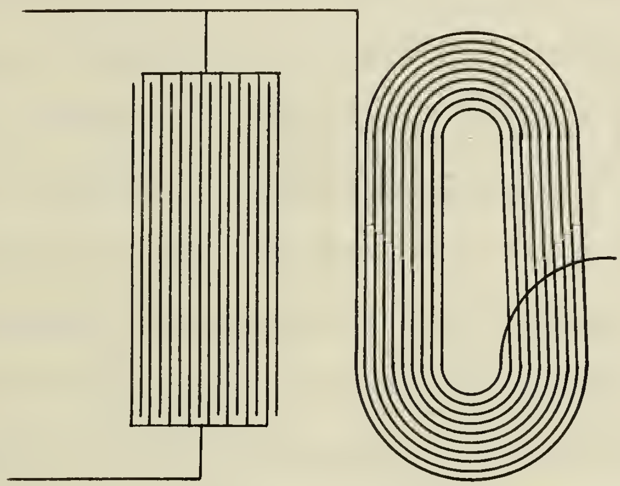

Fig. 86.-- The "Static Interrupter".

The "Static Interrupter" shown in Fig. 86 is simply a combination of a condenser and a choke coil very similar to the "Zig" lightning arrester. The choke coil and condenser are so connected to the circuit as to magnify the effect of the choke coil, as regards static waves, without causing a sensible disturbance in the normal operation of the circuit. The choke coil, which contains no iron, receives the full

force of the static waves which it is intended to check and should be, therefore, heavily insulated. The loss in the condenser varies as the square of the voltage and increases rapidly with the temperature. The capacities of condensers for static interrupters seldom exceed one tenth of a microfarad and thus their reaction on the circuit is practically negligible.

The static interrupter delays the penetration of the crest of the static wave but does not prevent the ultimate rise of potential, therefore it affords no direct protection against grounds although it permits the lightning arresters to act for longer periods. The interrupter performs a more important function in connection with the discharge of an arrester by protecting the apparatus from violent strains that may result from the abrupt grounding of the circuit caused by direct discharge, as the discharge of the arrester occurs when the potential is much above normal and may be carried momentarily much beyond ground potential on account of its oscillatory nature; the shock to the coil may be a severe one.

It is well known that considerable energy is dissipated by silent electrical discharges, known as corona, which are effected at very high potentials, and also that high potential disturbances may be prevented to some extent when a system is working at the so-called "corona voltage". Therefore, by employing conductors of relatively small section or of peculiar shapes, the formation of corona may be effected at any predeterminated voltage, whereby energy is dissipated

and dangerous surges are prevented.

At varying intervals, protecting conductors are inserted in series with the transmission circuit for the purpose of facilitating the formation of corona and thus preventing excessive voltages. These protecting conductors may be of relatively small section in comparison with that of the conductor which constitutes the transmission line or may have shapes that are peculiarly conducive to the production of corona. If the transmitting conductors are made of aluminum, a single protecting conductor of copper may be placed in series therwith without increasing the normal resistance of the line.

The older forms of lightning arresters have, as the underlying principle, the fact that an inductance or capacitance in a line acts as a reflector for electrical disturbances impressed thereon. By the use of the oscillating circuits connected to the line as shown in Fig. 87, the energy of moderate high frequency disturbances is completely absorbed by reason of the close inductive interlinkage between the primary and secondary windings of the air core transformers when subjected to high frequency impulses.

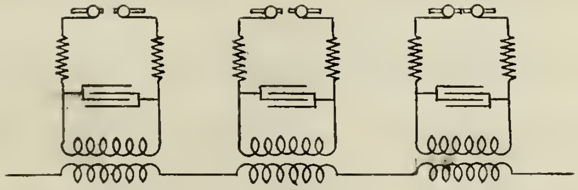

Fig. 87.-- "Non-Reflecting" Protective System for Transmission Lines.

ELECTROLYTIC LIGHTNING ARRESTERS

The electrolytic lightning arrester was first devised in England by Ferranti in 1901 but it was abandoned at a very early stage of its development. Later on, Mr. R. P. Jackson undertook its investigation and in December 1906 presented a paper before the American Institute of Electrical Engineers giving publicity to the principles and details of this type of protective apparatus. The electrolytic arrester has been ever since widely investigated. Two different types have been developed: the "Aluminum Cell" arrester and the "Liquid Electrode" arrester.

There are two commercial forms of "Aluminum Cell" arresters: those using cylindrical electrodes and those using conical and double conical electrodes.

Fig. 88 shows the cylindrical electrode or jar type aluminum arrester which consists simply of three hollow, concentric, aluminum cylinders supported rigidly from a substantial porcelain cover and held in a glass jar filled with the electrolyte. The leakage current through this arrester is only a few milli-amperes but the plate area of the cells is such that the arrester can safely discharge from 800 to 1000 amperes at double normal voltage. A fuse is usually placed in series with the arrester in order to protect it from unusual lightning discharges. When a number of jars are placed in series, it is good practice to shunt each one with a very

high resistance so that the voltage be equally divided among the cells. The evaporation of the electrolyte is prevented by a thin layer of oil on its surface.

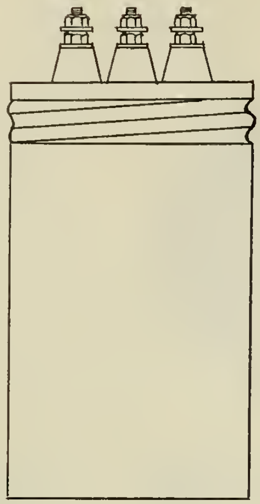

Fig. 88.- "Jar Type" Aluminum Cell Lightning Arrester.

Circuits as high as 2,600 volts direct current are protected by a number of these arrester units placed in series. This type of arrester is sometimes used on alternating current circuits, in which case a gap is placed in the discharge circuit.

Circuits of higher potentials can be protected by aluminum cell arresters using conical or double-conical electrodes. Fig. 89 shows in detail a double-conical aluminum tray. The advantages of this type of tray over its predecessor, the single-cone tray,(Fig. 90) are that in the former a greater area of plate can be exposed to the electrolyte and that more

effective cooling of the trays can be obtained by having a central circulation duct.

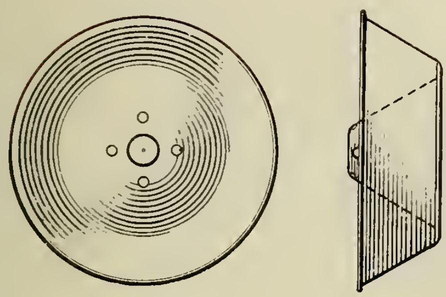

Fig. 89.- "Double-Conical" Tray for Aluminum Lightning Arresters.

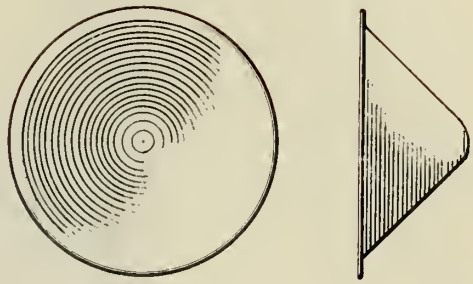

Fig. 90.- "Single-Conical" Tray for Aluminum Lightning Arresters.

The tray arrangement is particularly flexible to meet special conditions. Standard direct current arresters of this type can be used on circuits as high as 2,450 volts, but the standard alternating current arresters are fitted for circuits as high as 110,000 volts and special arresters are built for higher voltages.

Fig. 91 shows a tray structure used for voltages up to 6,600. The trays are spaced by porcelain pieces and held in place by treated wooden boards and insulating rods. The complete structure is placed into a bakelite-micarta lined tank which is then filled with a special oil of high dielectric strength.

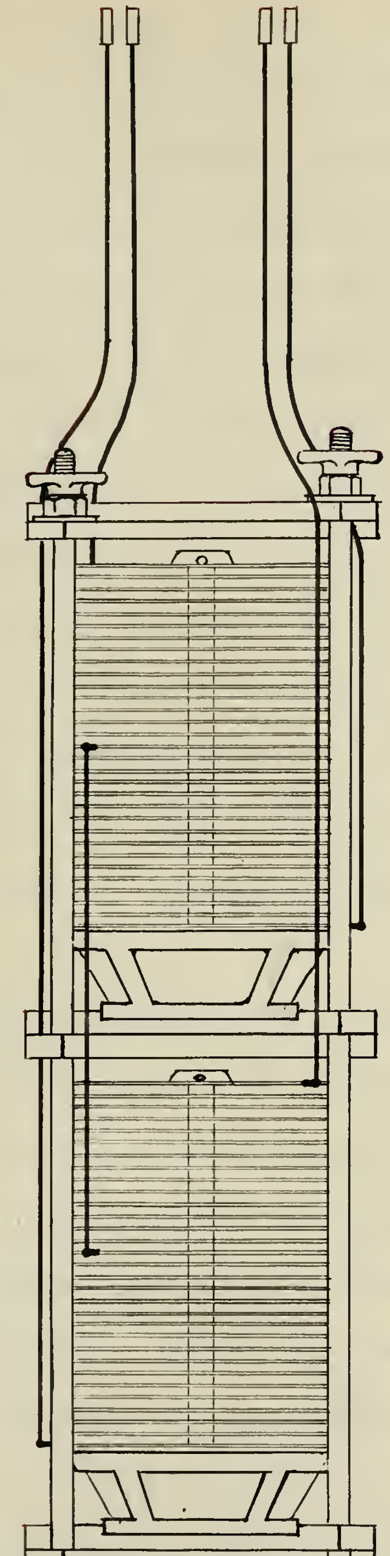

Fig. 91.-- Tray Structure for a
6,600-volt Aluminum Cell Lightning Arrester.

The principles of the aluminum cell were briefly discussed in Chapter III. The most useful characteristic of the aluminum cell lightning arrester is its critical voltage. This critical voltage depends on the formation of a film of aluminum hydroxide on the surface of the plates. The plates are put through chemical and electro-chemical treatments until the film is formed. After the arrester is assembled the film is gradually dissolved by the electrolyte but can be reestablished by a momentary application of normal potential. The film is composed of two parts: one hard and insoluble which apparently acts as a skeleton to hold the soluble part. The latter is perhaps composed of liquified gases. A momentary rush of current is required by the cell, when it has been disconnected for some time, in order to reestablish the soluble part of the film.

The mechanical construction of aluminum cell arresters is such that the electrostatic capacity of the trays is relatively large, and consequently, large charging currents are necessary even at commercial frequencies. The time phase of this current is nearly 90° with the potential and represents, therefore, an unappreciable power loss; but the deterioration of the plates is considerable. On this account, a spark gap should always be installed in series with the arrester when used on alternating current circuits. The deterioration of aluminum plates under continuous voltages is very small and therefore, arresters are often connected directly to the line, although the addition of a gap lengthens the life of the

arrester, if properly charged.

When a cell is connected permanently to a circuit, there are two conditions that may be distinguished as "temporary" critical voltage and "permanent" critical voltage. If the working voltage is less than the critical voltage specified by the manufacturers, there will be a rush of current when the voltage is suddenly increased by a small amount and the arrester will operate. In this case, the working voltage becomes the "temporary" critical voltage. After the rush of current, the arrester assumes a new critical voltage; that is, the thickness of the film is increased to meet the new conditions; but when the "permanent" critical voltage is reached, there cannot be any further thickening of the film.

The rate of dissolution of the film increases with the temperature. This accounts for its rapid dissolution after long discharges, in which cases the arrester should be charged as soon as it cools down.

The charging of aluminum cell arresters is generally done through horn gaps either with or without series resistance. No dangerous surges are produced by charging without series resistance although the inductive effect on parallel telephone lines is annoying. It is, therefore, advisable to use resistance in the charging circuit.

A simple rule to calculate the discharge rate of aluminum arresters at double potential# is to divide the excess

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#--The Charging of Aluminum Lightning Arresters. By E. E. F. Creighton. General Electric Review, April, 1913.

of normal potential by the resistance of the electrolyte (about .5 ohm per cell at 200 volts or a little less at higher voltages). This will give a minimum equivalent resistance that will damp the oscillations that may be created in one cycle of the natural frequency of the line. Series resistance is necessary because the equivalent resistance of the arrester does not limit the rush of current at charging, which may even damage the arrester itself. Besides, the rate of current flow with respect to time may be so great as to cause sparks across the potential terminals of current transformers and finally, the oscillations set up in the line may develop into serious surges.

The potential drop across the resistance, in charging, is in quadrature with the drop across the cells and consequently affects the magnitude of the latter very little but limits the charging current to the desired value. The amount of resistance permissible is that which reduces the potential across the cell by one per cent. Thus, the potential across the resistance must be about 14 per cent of the line voltage. And since .4 amperes is the allowable charging current for 60 cycle circuits, the resistance must be,

$$R = \frac{.14\ E}{.4} = .35\ E$$

where E is the line voltage.

The maximum possible initial current is then,

$$I_{max.} = \frac{E}{R}$$

Or simply: For 99 per cent of film voltage, the resistance may be numerically equal to 35 per cent of the Y potential of the line. At 25 cycles, this percentage may be doubled to give satisfactory operation.

TABLE I.

Arrester Potential Line-to-line	Charging Resistance per Phase	Resistance in Electrolyte per Phase	Equivalent Resistance in Film at Normal Potential, per Phase
2,300	133	2.4	500 to 2,000
6,600	382	6.4	1,500 " 6,000
10,000	580	10	2,200 " 8,800
13,200	760	13	3,000 " 12,000
20,000	1,160	22	4,400 " 17,600
25,000	1,450	34	5,600 " 22,400
33,000	1,910	48	7,800 " 31,200
45,000	2,600	65	10,000 " 40,000
60,000	3,500	88	14,000 " 56,000
80,000	4,600	115	17,600 " 70,400
100,000	5,800	145	22,200 " 88,800

Table I gives the charging resistance per phase, resistance of the electrolyte per phase and the equivalent resistance in film at normal potential per phase, for aluminum cell arresters commonly used under various potentials. The third column is based on a uniform spacing of .3 inch for medium and lower voltages. The spacing in high tension arresters is a little greater and therefore, the discharge rate is proportionally smaller.

The "Liquid Electrode" lightning arrester was invented by E. E. F. Creighton#. This arrester, like the electrolytic aluminum cell arrester, has the desirable feature of the critical voltage.

The "Liquid Electrode" arrester consists essentially of two metallic electrodes extended into a vessel containing a certain electrolyte of high conductivity. The electrodes may be dipped into the electrolyte, as shown in Fig. 91, or they may form a gap with it as shown in Fig. 92. When the electrolyte is placed under electric strains, it has the peculiarity of generating a counter-electromotive force which opposes the impressed voltage up to a certain definite value. This counter-electromotive force is not generated in the electrolyte but on its surface, in the arcs formed with the metal electrodes, so that it requires about 1,500 volts to maintain the current through the cell in spite of the fact that the electrolyte is extremely low.

The "Multigap" arrester works on the principle of rectification while the electrolytic arrester works on the principle of counter-electromotive force. Therefore, the former is only adaptable to alternating current circuits while the latter is adaptable to both direct and alternating current circuits. In the multigap arrester, during the first half cycle there is little obstruction to the current flowing in

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#--"New Principles in the Design of Lightning Arresters" By E. E. F. Creighton. Pro. A. I. E. E., April, 1907.

the arcs in the gaps, hence, it is necessary to have a series resistance to limit the dynamic current. In the liquid electrode arrester, if there is a gap between the electrodes and the electrolyte, currents as high as 1000 amperes can pass without forming an arc of dynamic current. When the electodes touch the electrolyte, it is necessary to introduce at least one spark gap in the circuit in order to hold back the line potential,(Fig. 94). Since the counter-electromotive force

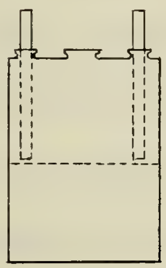

Fig. 92.- "Liquid Electrode" Lightning Arrester, Non-Touching Electrodes.

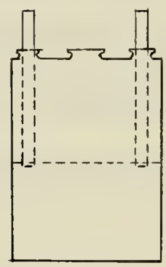

Fig. 93.- "Liquid Electrode" Lightning Arrester, Touching Electrodes.

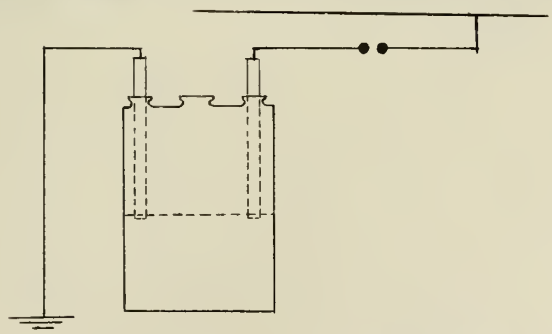

Fig. 94.-"Liquid Electrode" Lightning Arrester with a Spark-Gap in Series.

in the arrester limits the current; this single gap suffices even at high potentials. (100,000 volts.)

When the potential breaks across the gaps the current

rushes at short circuit rate. The current density at the electrodes is such as to start an arc which throws the electrolyte away from the electrodes and automatically lengthens the arc. The arc voltage is greater than the impressed voltage, consequently the arc dies out. The current starts at short circuit value but decreases at such a rate that no surges have been detected. The arc voltage of the liquid electrode depends somewhat on the length of the arc caused by the current.

The quantity of electricity that passes through the arrester, before the electromotive forces absorbed by the arc become effective, depends upon the amount of exposed surface of the metallic electrode. It can be increased by immersing the electrodes in the electrolyte.

The dielectric spark lag of the arrester circuit is very small since there is only one gap. The breaking potential is nearly independent of the frequency.

AUXILIARY PROTECTIVE APPARATUS

When a steep-front traveling wave is started on a line, it will be only damped by the line reactance and capacity and will continue its way until a concentrated reactance or capacity is met along the line. At such point, the wave will suffer a partial reflection as discussed in Chapter II. Reactance coils are now generally used for this purpose. The magnitude of the non-reflected part of the wave depends on the choking capacity of the reactance encountered. The steepness of its front is also correspondingly reduced. These effects are sometimes repeated by placing several coils in series.

Traveling waves are generally originated on the transmission lines and run towards the stations. When a traveling wave is partially reflected by a concentrated reactance, its potential is nearly doubled at the point of reflection, consequently the best location for choke coils is between the arrester connection and the apparatus to be protected.

The use of choke coils in transmission systems is in the nature of a compromise. If the reactance of the coil is too small, it will fail to hold back the waves of steep wave-front; and if too large, it will be costly and will spoil the regulation of the line.

There are two kinds of reactors on the market: choke coils and protective reactances.

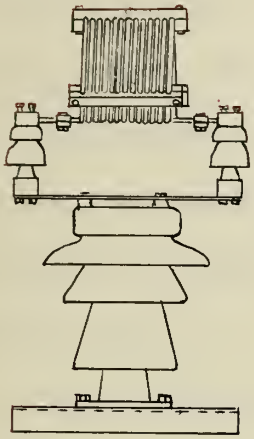

Fig. 95.-"Cylindrical Type" Choke Coil.

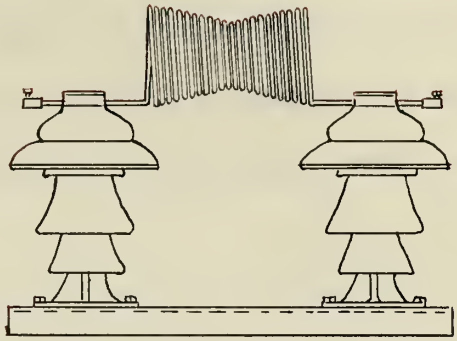

Fig. 96.-"Double-Cone Type" Choke Coil.

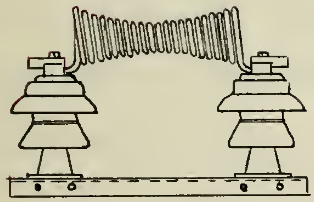

Fig. 97.-"Hour-Glass Type" Choke Coil.

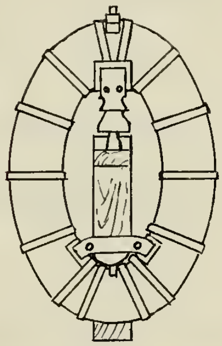

Fig. 98.- "Flat Type" Choke Coil.

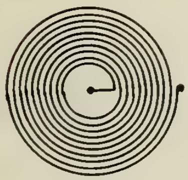

Fig. 99.- "Uncompensated Type" Choke Coil.

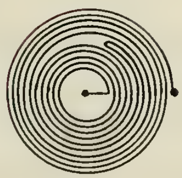

Fig. 100.- "Compensated Type" Choke Coil.

Fig. 95 represents a common type of cylindrical choke coil for high potential circuits. For low potential circuits, the wire is usually insulated and mounted on a wooden or porcelain core. For high potential circuits where the electric strains are very severe, the turns of choke coils should be insulated from each other by a dielectric possessing a high self-repairing power. Air fulfills this requirement very satisfactorily.

Fig. 96 shows the double-cone type choke coil and Fig. 97 the so-called "Hour-Glass" type. These two types are adaptable to high potential circuits. It has been found experimentally that a choke coil having its middle cross-section smaller than those at the ends is more effective than a cylindrical one of the same mean diameter and number of turns. The design of the double-cone and the hour-glass types is based on this principle.

The "Flat" type choke coil shown in Fig. 98 can be used on circuits as high as 29,500 volts and should be used indoors. For potentials as high as 70,000 volts, this type can also be used but the coil must be immersed in oil to insure proper insulation and cooling.

There are two classes of flat choke coils: uncompensated and compensated. Uncompensated coils consist of a simple spiral of copper conductor, as shown in Fig. 99; and compensated coils are a combination of a direct and a reverse spirals formed by the same conductor, as shown in Fig. 100.

By means of compensation, the magnetic field of the

coil, under working conditions, is almost negligible but the protection against high frequency oscillations is nearly as effective as that of the uncompensated coil. The compensated coils were devised by Mr. C. C. Chesney.

For coils of small current capacities, 80 per cent of the checking effect is due to the "skin effect" and 20 per cent to the inductance. For the same cross-section and length of wire, the greatest inductance can be obtained by winding a flat strap in a spiral form.

There are line choke coils especially designed to absorb high frequency oscillations by transforming part of their energy into heat.

The best type high frequency absorbing reactance is the one with distributed resistance between turns. A partially conducting cement is used, which serves both as mechanical support and as an electrical resistance, as shown in Fig. 101.

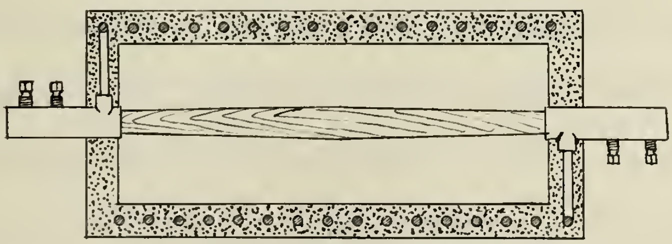

Fig. 101.-"Absorber" Type of
Choke Coil.

As the surge potential piles up on each turn of the coil, it forces current through the distributed resistance

between turns, the recoil from the stored magnetism is thereby avoided and part of the surge energy is transformed into heat. The steeper the wave front and the higher the frequency, the more efficient is the absorption of surge energy. In other words, the more severe the surge, the more it is forced through the resistance.

Fig. 102.- Method of Breaking up Traveling Waves in Transmission Lines.

The small arrows in Fig. 102 indicate the flow of excess energy from line to line as a traveling wave encounters the absorbing choke coils. When a traveling wave encounters one of the coils, three things take place: it is partially absorbed by the shunting resistance from turn to turn; it is partially reflected by the inductance of the coil; and it is partially transferred to the adjacent wire by the dielectric displacement, (as indicated by the arrows.) This displaced charge is divided into two parts, one of which travels in the opposite direction to the original wave. A traveling wave is thus broken up into many parts and its energy silently dissipated.

Reactance coils differ from choke coils simply in the

number of turns. Fig. 103 illustrates the construction of a typical "Protective Reactance" It consists simply of a heavy double conductor, (any number can be used) wound in the shape of a coil and held in place by porcelain pieces of special design. There are protective reactances on the market that

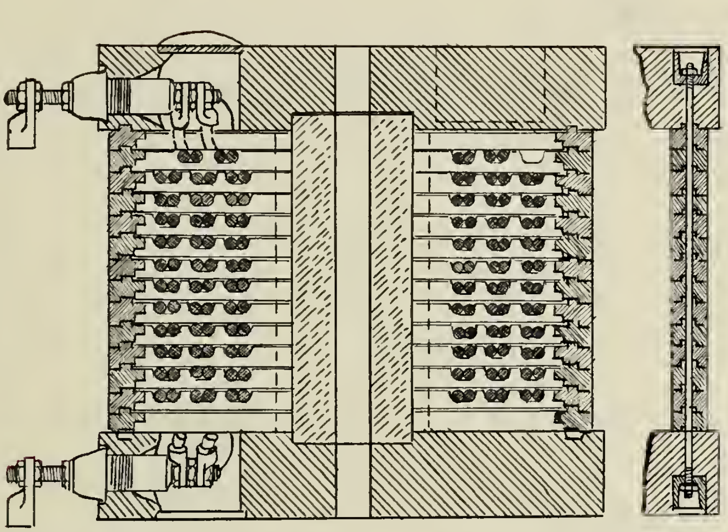

Fig. 103.- Details of a "Protective Reactance".

are held in position by a semiconducting cement which gives them absorbing qualities similar to those of the choke coil previously described.

The main function of protective reactances is to limit the amount of current that can flow in case of short circuit to apparatus. By thus limiting the flow of short circuit current from one part of the system to another, the trouble is localized to the damaged section without materially impairing the rest of the system. In addition to limiting the short

circuit current, the reactance coils afford considerable protection to the system by localizing high frequency oscillations and thereby preventing them from spreading over the entire system.

C H A P T E R V I.

LIGHTNING PROTECTION FOR TRANSMISSION AND DISTRIBUTION SYSTEMS.

OVERHEAD LINES

There are two distinct types of transmission or distribution lines: overhead and underground. Each one of these types of lines is subjected to different lightning troubles and consequently, requires different methods of protection.

Atmospheric electrical phenomena rarely disturb underground transmission lines on account of the shielding effect of the ground, but they are the cause of most of the disturbances on overhead lines.

Different regions on the earth's surface are susceptible to lightning disturbances in a varying degree. In designing transmission lines, therefore, care should be taken to avoid, as far as possible, regions where lightning disturbances are exceptionally severe. Oftentimes, conditions are such that there is no choice of paths, in which cases the line insulation should be designed to withstand the exceptional stresses to which it will be subjected andadequate protective devices should be installed along the line as well as at the stations or substations.

There are three principal methods of protecting transmission lines:

1.-- By the use of overhead ground wires.

2.-- By the use of line arresters.

3.-- By the combination of line arresters and ground wires.

THE OVERHEAD GROUND WIRE

The overhead ground wire was first used by C. C. Chesney on the original polyphase transmission line at Housatonic, Mass. about 1891. Shortly afterward, the Montreal Light Heat and Power Co. used it on the Chambley Falls-Montreal line. The favorable results reported by these users induced many other companies to install overhead ground wires on their lines. To-day the ground wire is advocated by our most prominent engineers.

The three recognized uses of ground wire are:

1.-- Lightning protection.

2.-- Mechanical support for towers or poles.

3.-- A test circuit.

Only the first use will be considered in our discussion.

Ground wires, as used for lightning protection of transmission lines are either vertical, or else horizontal and vertical. The vertical ground wire is nothing more than a lightning rod.

It has been found, through years of experience, that a well grounded conductor strung along the line poles will

generally save the latter in cases of direct lightning discharge. This type of pole protection is now the standard for telegraph and telephone circuits, where every fifth pole is protected in this way.

The protective value of the vertical ground wire is not affected when the latter is used in combination with a horizontal wire. Where this combination is used, the vertical wire becomes an essential part of the protecting circuit.

The electromagnetic effects of vertical ground wires, when connected to the horizontal ground wire, have so far been given very little consideration. When lightning discharges to ground occur in the neighborhood of a protected line, there will be an induced charge on all the vertical conductors in the vecinity. The parallel action of all these conductors creates a wave on the ground wire, which in turn induces one on the line. The wave on the ground wire is soon discharged through the grounding wires, but that on the line wires will merely be damped and may reach the station arresters. Lines mounted on steel towers are particularly susceptible to such troubles.

There is a great diversity of opinion about the use of horizontal ground wires for protection of transmission lines.

The working principle of the ground wire is that of Faraday's "cage"; that is, of inclosing the line within a grounded shield. This principle does not seem to be clearly understood by some engineers. Lines are now in operation with

a grounded horizontal wire 10 to 15 feet below the line wires. It is true that such a construction is cheaper and that there is no danger of the groundwire falling on the lines and causing short circuits, but this ground conductor fails to perform its primary function, namely that of protection against atmospheric electrical disturbances.

From Faraday's principle, it is evident that the best results are obtained by placing the ground wire above the line conductors. The protective value of this conductor lies in the tendency to prevent the arc flame from being blown between the phases of the power wires, which would cause a short circuit. The extremely intense electric force and potential gradient of the path of the direct stroke of lightning brings the usefulness of the lightning rod into question. Even if the rod is high enough to keep the ionized flame away from the power wires, it must yet be determined if the electric field induced on the power wires adjacent to the lower end of the lightning rod is not great enough to cause a side flash from the rod to the power wires, on account of the so-called isolated capacitance of the power wires.

The main functions of lightning rods are: First, to keep the conducting arc vapors of the direct lightning stroke away from the power wires, and second, to prevent a bolt from striking midway between the poles.

Where steel towers are used, the projection of these above the line wires serves sometimes as a substitute for lightning rods. The higher the rod or tower above the line

the less the chance of a direct stroke reaching the line wire.

There are several factors to be taken into account in the process of determining the protective value of a ground wire:

1.-- The strength of electric field in the neighborhood of the line wire.

2.-- The direction of the gathering charge in the cloud.

3.-- The screening effect obtained by the use of several wires with and without ground wires.

4.-- The initial momentary potential induced on a wire at the instant the cloud discharges to earth.

5.-- An instant after lightning discharge has taken place, the sudden increase in capacitance between the power wire and the adjacent parallel ground wire.

6.-- The effect of number and location of parallel ground wires.

7.-- The effect of electromagnetic induction between the horizontal part of the ground wire and the parallel power wires, in which the energy of the lightning charge on the ground wire is more or less transferred to the power wires instead of being dissipated in the earth. High frequencies are produced in this transformation.

8.-- The gradual transferrence of the charge which travels along the power wires to successive sections of the ground wire and its dissipation in the earth.

The quantity of electricity induced on a wire is only

slightly affected by the diameter of the latter. This leads to the conclusion that a small wire is nearly as effective as a more expensive large one.

The instantaneous value of the induced potential on a circuit is independent of the number of wires used. Even the ground wire may take the full potential and give no relief at the first instant.

The two factors in the electrostatic protection of an overhead ground wire are screening and increase in capacitance of the line wires. The presence of the ground wire reduces the charge induced on each of the power wires and incidentally, after the cloud discharges to earth, the ground wire takes over part of the charge of the power wires, and in taking it, the capacitance of each power wire is increased. Therefore, with the same quantity of electricity, the potential is reduced by this increase in capacitance.

As the charge runs to earth on the ground wire at the instant the cloud discharges, it induces a considerable voltage on the line wire by electromagnetic induction. Consequently, part of the protection afforded by the ground wire is lost by the fact that the energy oscillates in the ground circuit and is transferred to the power wires.

Traveling waves are more or less absorbed as they pass each successive loop of the ground wire, depending on the resistance of the earth connections.

From a theoretical standpoint, a single ground wire should be placed as near as practicable to the power wires,

in order to obtain the greatest electrostatic protection.

In installing two overhead ground wires, the greatest advantage can be obtained by keeping them as far apart as possible, that is to say, on the opposite sides of the line.

J. F. Vaughan# conducted a very interesting series of experiments to investigate the protective value of some transmission line protective devices.

A line of the Taylor's Falls transmission system was used for the experiments. The line is 40 miles long and through rolling country but only 9 miles of it were used for the experiments. The chosen section was especially subjected to lightning disturbances.

The plant consists of four 2500 kilowatt, 2300 volt, 60 cycle, 3 phase generators and banks of transformers that raise the voltage to 50,000 v. for transmission.

The line conductors are 4-0 semi-hard-drawn copper cables supported on 14 inch four part insulators arranged in a 6-foot equilateral triangle.

The protection of the power house and substations consists of low-equivalent multigap arresters and oil insulated choke coils, supplemented at a substation by a set of aluminum cell arresters. All transformers are protected on the low tension side by static discharge gaps.

The line protection consists of horn type arresters. A single gap is used at substations and a double gap at the

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#--"Comparative tests of lightning protection devices on the Taylor's Falls transmission system"-Pro. A.I.E.E. 5-1908.

station.

Four types of overhead ground wires were installed in half mile lengths alternating with half mile sections of unprotected line.

Type A.-- Two wires mounted on a cross-arm, 5 feet apart on each side of the top line wire and about 18 inches below it.

Type B.-- Two wires supported on stands of 1.25 inch iron pipe, 6 feet apart and 18 inches above the top line wire.

Type C.-- One line wire on knobs attached to the ground pipe near the center of the delta.

Type D.-- Two wires in the same position as type B but supported on iron pins.

Different types of lightning rods were also installed.

Type A.-- Rods of 1.25 inch galvanized iron pipe attached to the poles and extended by tridents of copper wire.

Type B.-- Rods of 1.5 inch galvanized iron pipe mounted on separate poles 20 feet from one side of the transmission line topped by tridents of copper wire and extending 25 feet above the line wires.

The rod poles were placed in the center of the alternate spans.

Type C.-- Same as type B but spaced three rods to four spans.

Type D.-- Same as type B but spaced 1000 feet apart.

The ground connections were mounted with two ground plates 20 feet or more apart to insure wet ground and increase

the discharge area.

To study the stresses in line insulators each insulator pin at every third pole was grounded through a tell-tale box supplemented by choke coils shunted with tell-tale gaps cut into the lines at various points. After a great number of grounded insulator failures the grounds were removed from every other mile of line.

The results of the experiments so far indicate that: The principal trouble is from temporary or permanent break-down of line insulation by static charges induced in the line by passing storms.

Direct strokes between cloud and ground may occur at any time; although there were several cases of damage so caused during construction, the first season's operation gives evidence of only one case and that without damage.

The induced charges are highly concentrated. Insulators are often bridged by heavy discharges whose disruptive effect tends to shatter but rarely to puncture them, often without line current flowing. If line current follows, it may only temporarily ground or short-circuit the line.

Arcs established by the insulator spillovers or leakage of charging current through damaged insulators may burn the pole structures or further damage the insulators and even fuse the line wire. Such disturbances may occur anywhere on the line but with a preference for exposed heights and to a less degree to wet lowlands.

There is no evidence of surges other than the direct

effect of grounds or short circuits, nor of stress at any definite points on the line such as from reflected or standing waves.

Top insulators and to a less extent those on the cross-arm, apparently are more liable to damage although the cases are not sufficiently frequent to be conclusive.

Grounding of insulator pins by tower structures or ground conductor has comparatively little effect in assisting insulator breakdowns.

Overhead ground wires are of decided value in shielding the line from induced static charges and in preventing insulator breakdowns.

The lightning rod alongside the line was effective in preventing line damage only in the case of direct stroke.

A grounded conductor running down the pole is of decided value in preventing splintering of the pole.

The selective resistance multigap type arrester is effective in disposing of ordinary disturbances. The aluminum cell arrester is, in general, more sensitive and freer in discharge than the multigap arrester.

Horn arresters of the series gap and selective resistance type are rarely sensitive to static discharges of low periodicity, but they are of special value as emergency devices to relieve the station arresters in case of abnormal discharges. They may be adjusted to be fairly sensitive so that their operation will not cause interruption of service.

The use of the tell-tale paper system is essential in

following the action of station protective apparatus and is of decided value in studying line stresses and the effectiveness of protective devices.

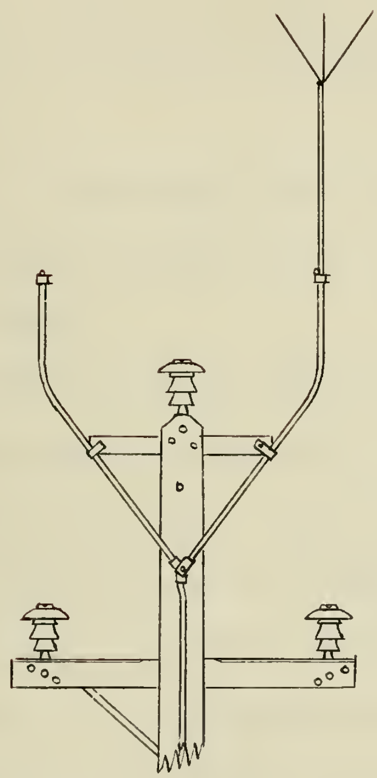

Fig. 104.--Arrangement of Line Protective Devices.

The results of the above experiments led to the recommendation that the overhead ground wire construction, as shown in Fig. 104 be extended about 15 miles in sections covering both ends of the most exposed parts of the line; that the use of horn arresters be continued and further adjustments studied; that

the rest of the station and line protective apparatus be left as it is; and that the present system of tell-tale paper and other records be continued during the coming season.

It was also found by these tests that line-to-line disturbances are pronounced and are generally of higher frequency than those from line to ground. Line-to-line protection is therefore advisable in conjunction with the protection to ground.

The degree of protection that a line ought to have depends on the severity of lightning in the region through which the line traverses.

A single overhead wire grounded about every 500 feet for average conditions, or every pole for extraordinary conditions, will offer sufficient protection from atmospheric disturbances. Such practice is not adaptable to systems where reliability of service is the prime consideration. In such systems from two to six grounded wires should be installed on the lines and adequate protectors placed at the stations and substations.

When transmission lines pass through regions particularly subject to lightning disturbances, they should be protected at the region and at the entrance and exit of the line. The protection in such a region may consist of standard station arresters in conjunction with horn arresters and choke coils and a sufficient number of grounded conductors placed on the towers or poles and, if possible, two parallel grounded conductors simply laid on the tops of the trees on

each side of the line right-of-way. These latter have been found very effective in choking the electrostatic induction from the trees at each side of the line. Sometimes the station arresters can be omitted but, under such conditions, horn arresters should always be installed. The main function of these arresters is to protect the line insulation.

It is often argued that the breaking of short circuits formed by these arresters may cause more damage than the original disturbance. But generally this is not the case because if the arrester is not in the circuit, the over-potential of the line discharges over the insulators or through them by punctures. In this case, the breaking of the arc will have the same effect as with the arresters and the system is similarly disturbed. But in the case of puncture the arc may hold and keep a short circuit on the line in neutral grounded systems. The line must, therefore, be shut down for repairs and usually after long searches, the damaged insulator is found and replaced. If the neutral is not grounded, the line may continue its operation for a short time perhaps until the effects of the arc (high frequency oscillations) develop into additional and more complicated troubles. Horn arresters along the lines are, therefore, advisable even if their operation is not entirely satisfactory.

L. C. Nicholson# proposes the use of a scheme to protect insulators from the damage caused by flashovers. It con-

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#-A Practical Method for Protecting Insulators from Lightning and Power effects. Pro. A. I. E. E., March, 1910.

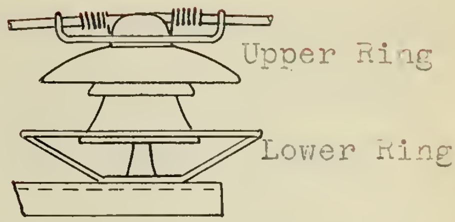

Fig. 106.- Pin Insulator Protected by Metal Rings.

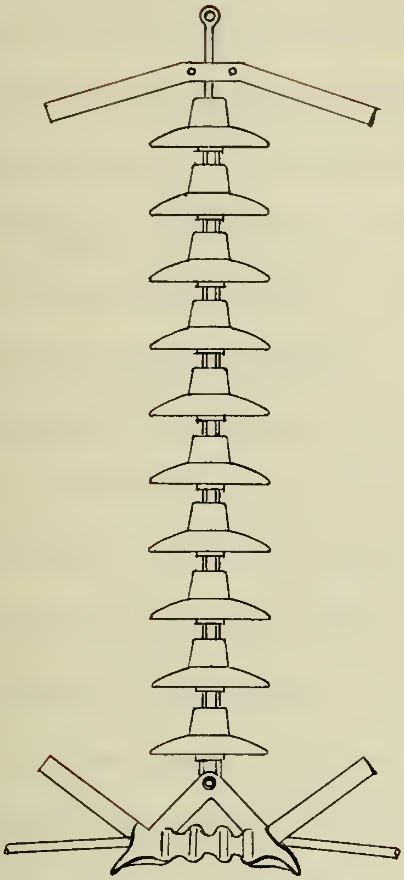

Fig. 105.- Suspension Insulator Protected by Arcing Bars.

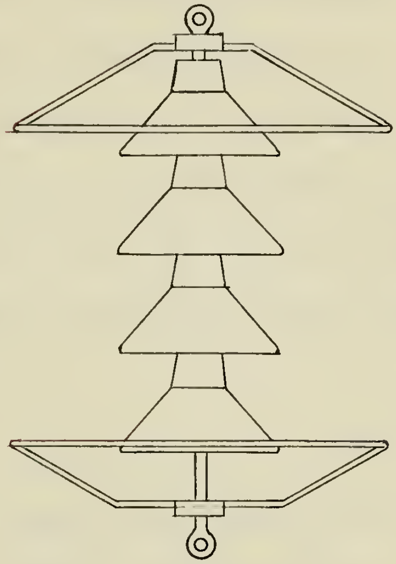

Fig. 107.- Suspension Insulator Protected by Metal Rings.

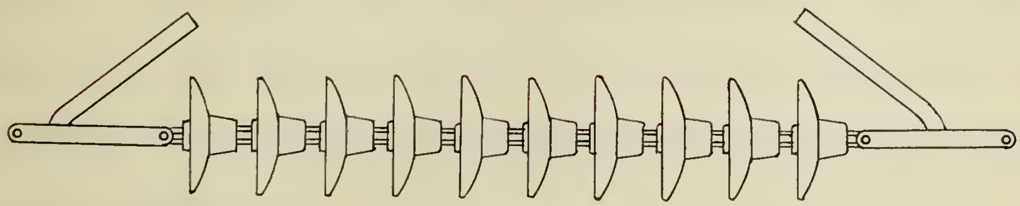

Fig. 108.- Strain Insulator Protected by Arcing Bars.

sists of protecting rings that can be attached to pin or suspension type insulators as shown in Figs. 106 and 107. These rings serve as electrodes and prevent the power flash, that often follows lightning discharges, from coming in close contact with the insulator and thus preventing puncture or shattering. Protecting rings of this type were installed on some insulators of the 60,000-volt line of the Niagara, Lockport and Ontario Power Co. and in a certain season, the failures of insulators with rings were about 3 per cent of the total while 22 per cent of the unprotected ones failed during the same season. These results indicate that the rings, although not entirely satisfactory, decreased appreciably the number of insulator failures.

The suspension and strain insulators of the 150,000-volt transmission system of the Pacific Light and Power Corporation# are similarly protected by arcing rods as shown in Figs. 105 and 108. These devices have, so far, given good service. There have been some cases of shattered insulators due to the blowing of the arc against the insulator by strong winds.

Choke coils and either horn or other rugged type of lightning arresters should be installed on the line where approaching and leaving points of dangerous regions in order to prevent disturbances there originated from spreading over the entire system.

The question of grounding the neutral of transmission

#-- 150,000-Volt Transmission System. By Edward Woodbury. Pro. A. I. E. E., September, 1914.

lines is of particular importance as concerns lightning protection. The arguments in favor of grounding the neutral are, in brief: that the potential of the line as a whole with respect to the ground is kept about constant; and that any gradual accumulation of charge on the line is easily discharged. But the argument against grounding is that which places continuity and reliability of service above every other consideration, even at an increased risk of the line insulation.

Reliability of service is becoming more and more important with the present tendencies of centralization of power.

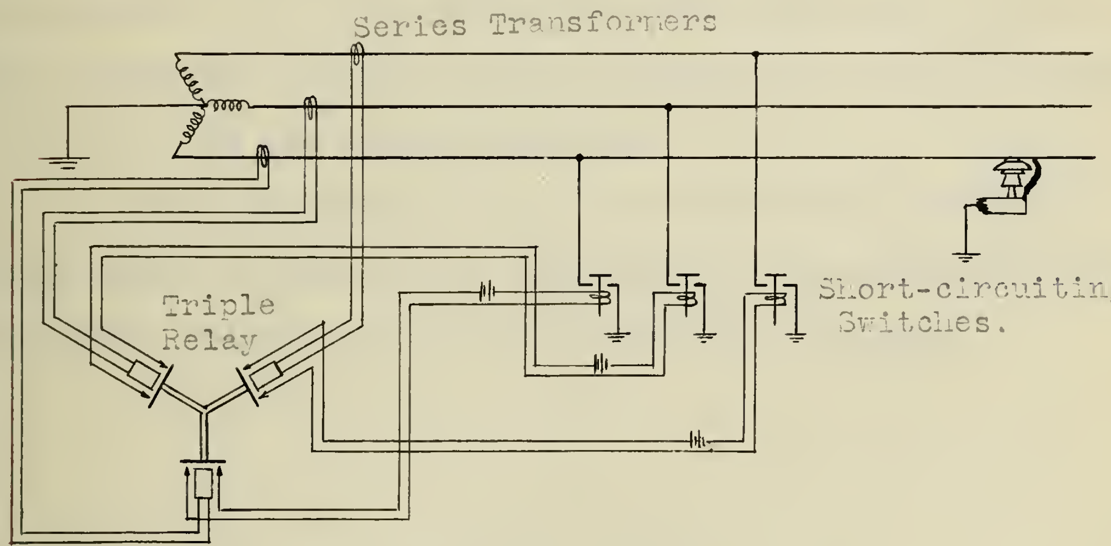

Fig. 109. The "Arcing-Ground
Suppressor".

Grounded neutral systems can be protected against insulator spillovers and break-downs by means of the "Arcing-Ground Suppressor" shown diagrammatically in Fig.109. It consists essentially of a relay operated by current transformers placed on the power lines. When for any reason whatever,

an arc is established around an insulator, the short circuit current operates the relay of the particular line. This relay in turn, energizes the tripping coils of an oil switch which short-circuits the line at the station. The switch stays closed only long enough for the insulator arc to break so that the system reassumes its normal conditions immediately afterward. The relay cannot operate two switches at the same time. In cases of punctured insulators the arc may be reestablished when the power is again thrown on the line. If such is the case, the relay operates again, and if the arc is still re-established, the relay holds the short-circuiting switch closed and operates an alarm for the attendant who must then disconnect the line and have it repaired.

This scheme is giving very satisfactory results in many modern systems and is therefore to be recommended where troubles of this nature are of frequent occurrance.

UNDERGROUND LINES

Underground lines have entirely different characteristics from those designed for overhead operation. Underground transmission potentials have, so far, been limited to about 20,000 volts.

The inductance of these lines is comparatively lower than that of overhead lines, while the capacity is correspondingly greater. This concentration of capacity makes underground

circuits particularly susceptible to internal lightning disturbances.

In systems where a combination of overhead and underground lines is used, special attention should be given to the protection of the junction of the two types of lines.

The large capacity of underground lines when in series with concentrated reactances such as choke coils gives the system a great susceptibility to the production of resonance. On the other hand, choke coils are indispensable to hold back disturbances tending to pass from one line to the other. Consequently, a compromise is made by forming a choke coil out of the end of the cable itself. Such coils are usually immersed in oil. The lightning arresters should be placed on both sides of the choke coil in order to discharge disturbances reaching the coil from any direction. When the insulation of a cable is broken and an arc follows the discharge, very destructive periodic oscillations are originated, as discussed in Chapter III. Such break-downs generally occur at defective joints or defective insulation anywhere along the cable. The location of such troubles is naturally a very difficult task when detective relays are not used in the system. Such relays serve not only to localize the trouble but to disconnect the damaged cable and to warn the attendant in the station.

For minor disturbances in cables, such as the formation of static, the static discharger or the aluminum cell have given fair satisfaction. The static interrupter is also used for this purpose.

The protection of underground systems by arresters containing spark gaps is still open to discussion on account of the greater susceptibility to lightning disturbances due to the combination of the arc phenomena with the characteristics of the line.

Where continuity of service is not the prime consideration, a very simple method is used to protect grounded overhead and underground lines. It consists of a relay operated by a series transformer in the ground connection of the neutral and controlling the tripping coils of the line circuit breakers. The common practice of disconnecting the line in case of trouble often causes disturbances which are perhaps more serious than the original ones. When the load consists mainly of synchronous machines, these will act as generators when the line is disconnected. The frequency of the impressed voltage naturally decreases and either the fundamental wave or its harmonics may reach the surge frequency of the line and cause enormous line potentials by the production of resonance. This trouble is overcome by installing under-potential relays and circuit breakers at the load end of the line.

The question of the deterioration of porcelain used for line insulators has been a subject of considerable discussion.

The properties of solid dielectrics were discussed in Chapter III. In brief, porcelain and assembling cements are subject to deterioration when placed under potential strains. On account of this continuous deterioration, line insulators

ought to be tested periodically. Whatever device is used for this purpose should have the following characteristics: it should be cheap both as to first cost and as to methods of use and should be reliable within practical limits. Too much expense, either in first cost or in labor involved, could not be put into this class of work without approaching the point where it would be more economical to install new insulation throughout.

As yet, only three methods of testing insulators already in use on the line have been suggested:

1.-- The oscillation transformer.

2.-- The "Megger" system.

3.-- The direct use of the telephone receiver.#

The use of the oscillation transformer is recommended by E. E. F. Creighton and clearly outlined as to connections and adaptations##. The data given in the discussion indicate that it is very satisfactory as a high frequency test and capable of being made very severe. Its availability and simplicity as a laboratory method for new insulators or those that have been removed from the line is clear, but its adaptability to service in the field is not so evident, presenting many difficulties. In the first place, in testing insulators on a line in actual service, it would be necessary to disconnect the line during the period of test, or to remove a quantity

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#- "Testing Defective Insulators on High Tension Transmission Lines" By B. G. Flaherty.- Pro. A.I.E.E., Aug.,1916
##- Pro. A. I. E. E., Feb., 1915.

of insulators from the line, crate, transport, uncrate, test and replace in the system, making the test prohibitive in cost. Also in attempting field work, a considerable crew would be required to handle and operate the apparatus and to make connections to each individual insulator, removing the line wire for the test. Another difficulty would be the source of current for the testing apparatus at all points on the line. These difficulties make the method impracticable for field work.

The megger test has become very widely used throughout the country, especially on suspension insulator work. T. A. Worcester[#] gives a thorough statement of the uses and limitations of this means of locating defective insulators. His main deduction is that it is not unconditionally reliable, being primarily a measure of the resistance which may be practically 'infinity' on a broken or punctured insulator unless the contact is made directly to the defect and the latter is made conducting by the application of moisture. Another objection to the use of the megger for this purpose, is the necessity of 'killing' the line under test for considerable periods and the use of a crew of men to make connections and to remove the line wires from the insulators. It seems more particularly adaptable for testing separate units of suspension type insulators.

The use of the telephone receiver in the detection of

#-- General Electric Review, -June, 1914.

defective insulators is mentioned by M. T. Crawford# and it is with the development and use of this method that the telephone detector was deviced. The apparatus, as developed for use on wooden pole lines, consists simply of a double-head set telephone receiver. The flexible cord used for connections is fastened by a small nut to the lineman's spur at one end, this serving as a ground terminal; and by a double connector to a large wire run through a bamboo stick and sharpened to a point for contact to the pole or cross-arm; i. e. shunting a portion of the current flowing in the pole through the receiver to ground. This, with the lineman's spurs and belt and a proper note-book constitutes all the equipment necessary for locating defective insulators on pole lines using pin type insulators.

For use on steel tower lines having pin or suspension type insulators, the upper terminal of the test circuit is extended to a miniature wireless antenna either in the form of spokes of a wheel or a thin circular plate. This device is used to explore the electrostatic field in the neighborhood of the insulator instead of measuring the actual current flowing through it. The disc or antenna is protected by an insulating cage of such dimensions as to give a clearance of four times the needle gap spark value for line voltage to ground.

Weather conditions have considerable influence on this kind of testing work through their effects on both the insu-

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#--Pro. A. I. E. E., Aug., 1914.

lator itself and the working conditions of the test apparatus. Rainy weather increases the leakage over the insulators, especially if there is a deposit of dust or any foreign matter, to such an extent that the exercise of a good deal of judgment of these effects is necessary in testing to keep from condemning many good insulator units.

C H A P T E R   V I I

PROTECTION OF STATION AND SUBSTATION EQUIPMENT.

STATION EQUIPMENT

Station equipment is subject to disturbances originating in the station itself and to those coming from the transmission and distribution lines.

Disturbances originating in the station consist of oscillations of high and medium frequencies. In the latter type of oscillations, the fundamental or lower harmonics of the impressed voltage may participate. High frequency oscillations are produced by arcing grounds through defective insulation, accidental short circuits or grounds.

Arcing grounds through defective insulation may occur in the stationary or the rotating equipment. In either case, the faults may be detected by having an alarm operated by a series transformer relay placed on the grounding conductor of the apparatus to be protected. The relay may directly operate the tripping coils of the oil switches connecting the apparatus to the main circuit.

Under certain conditions, as discussed in Chapter III, arcing grounds may create a continuous rise of potential on the steel frame of the station building if this is not well grounded. When the potential reaches the disruptive value

of some weak point it will discharge the entire stored energy. This disturbance may give rise to oscillations of medium frequency.

Accidental short circuits may be taken care of by circuit breakers operated by time-limit relays.

Sudden variations of load and the operation of switches generally cause oscillations of relatively low frequency. Such can be avoided, to a certain extent, by the use of protective reactances or static interrupters.

The static interrupters should be placed between the apparatus to be protected and the switches since switching is the main cause of static strains.

Fig. 110 illustrates a method of protecting single-phase transformers in which the interrupter is grounded to the transformer core and also to the middle point of the secondary. This type of protection often gives rise to arcing grounds to the transformer case. Fig. 111 shows another method of connection in which the interrupters are connected directly to ground. Figs. 112 and 113 illustrate simple methods of protecting sets of transformers connected in delta and star respectively. Fig. 114 shows the connections of the static interrupter as applied to transformers connected in T. And Figs. 115 and 116 show two types of generator protection.

The static interrupter is particularly suitable for use in combination with lightning arresters on account of the magnified effect of the interrupter choke coil. With such a combination, disturbances, whether originated in the station

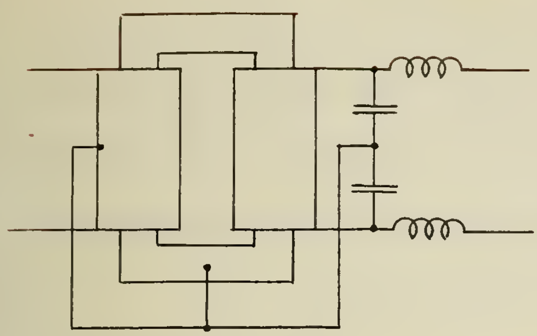

Fig. 110.

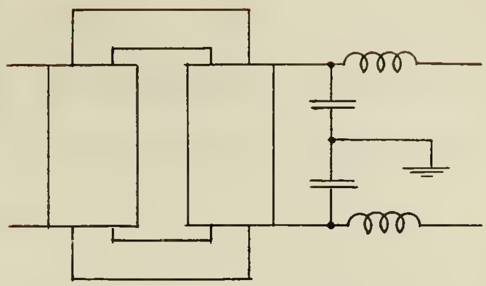

Fig. 111.

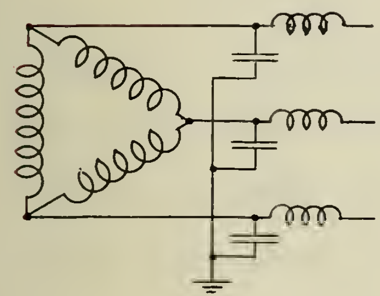

Fig. 112.

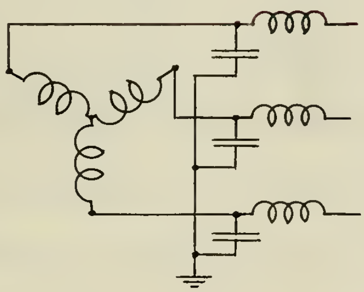

Fig. 113.

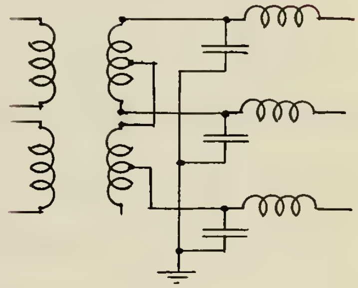

Fig. 114

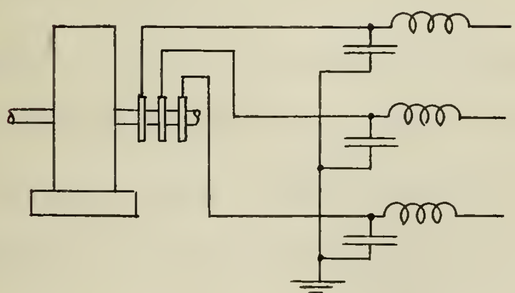

Fig. 115.

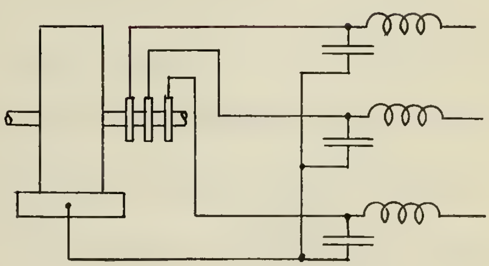

Fig. 116.

or in the line, can be easily taken care of.

The use of protective reactances was discussed in Chapter V. It should be added, however, that they should be placed as close as possible to the apparatus to be protected. In stations distributing alternating current, protective reactances should be installed:

1.-- On the leads of generators or transformers feeding busbars.

2.-- On the busbars between different sections of busses.

3.-- On feeder circuits fed from the busbars.

Protective reactances so located fulfill the main functions of limiting the amount of current that may flow from any part of the system into a short circuit in the apparatus or connections inside the station or close to the station. With some of the present larger power systems it is evident that the momentary overload capacity caused by short circuits, surges or lightning must be enormous. Should this vast amount of current concentrate at one point, the generators or transformers supplying the system would be subjected to mechanical strains created by the resultant large magnetic fields, which would tear them to pieces. Protective reactances also make the circuit more reliable for synchronous operation. High frequency oscillations are very effectively choked by these reactances and are, therefore, confined to the defective sections of the system. Fig 117 shows a particular layout of protective reactance coils.

Small stations can obtain adequate protection against disturbances originated in the station by installing choke coils of the absorber type instead of those of the common types. These choke coils will absorb very effectively all minor disturbances but in any case static interrupters should be preferred.

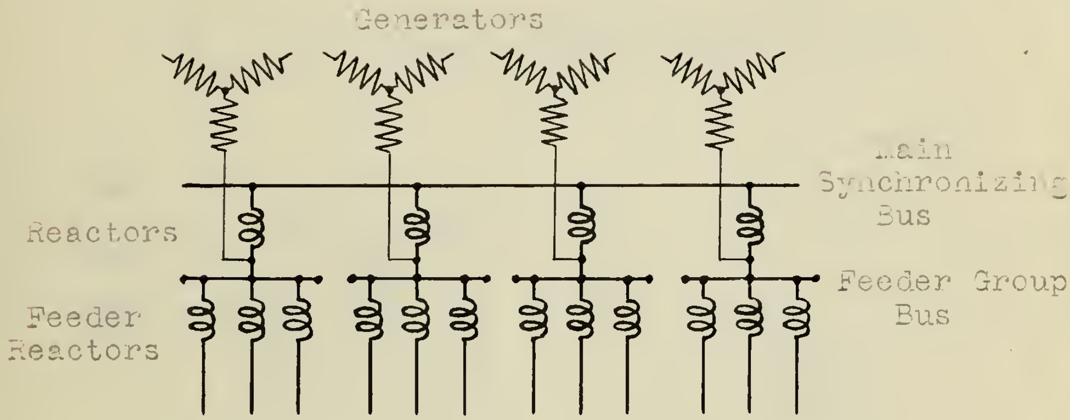

Fig. 117.-- One line diagram illustrating the use of "Protective Reactances".

The greatest share of the disturbances in stations come from the transmission and distribution systems. Consequently, particular attention should be given to protection against incoming disturbances. In order to reduce their number and magnitude the distribution and transmission systems must be thoroughly protected.

The use of reactance or choke coils to impede traveling waves from reaching the power equipment in stations

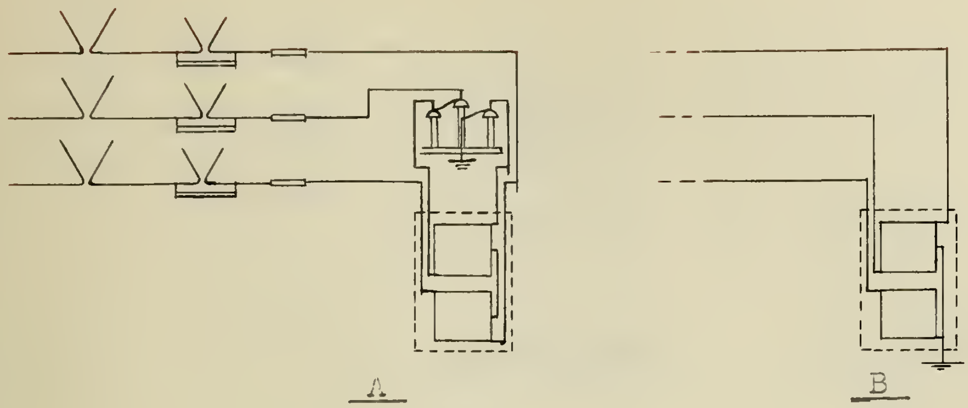

Fig. 118.- Aluminum Arrester Connections.
(2,200 to 6,600 volts.)

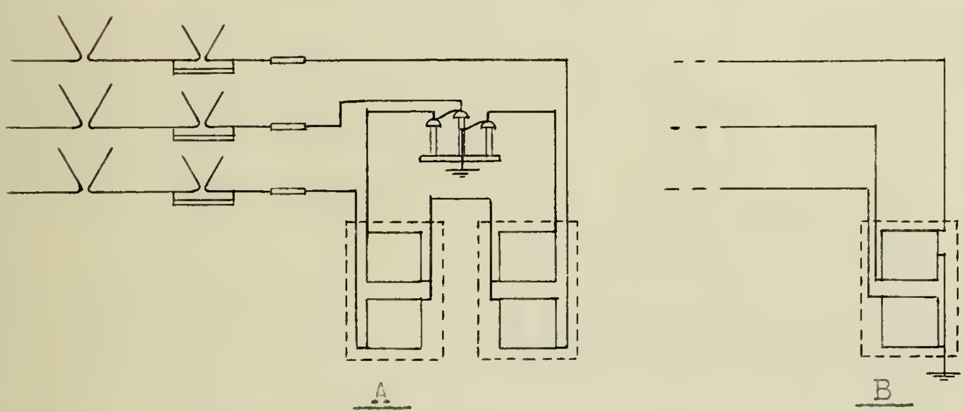

Fig. 119.- Aluminum Arrester Connections.
(6,600 to 13,200 volts.)

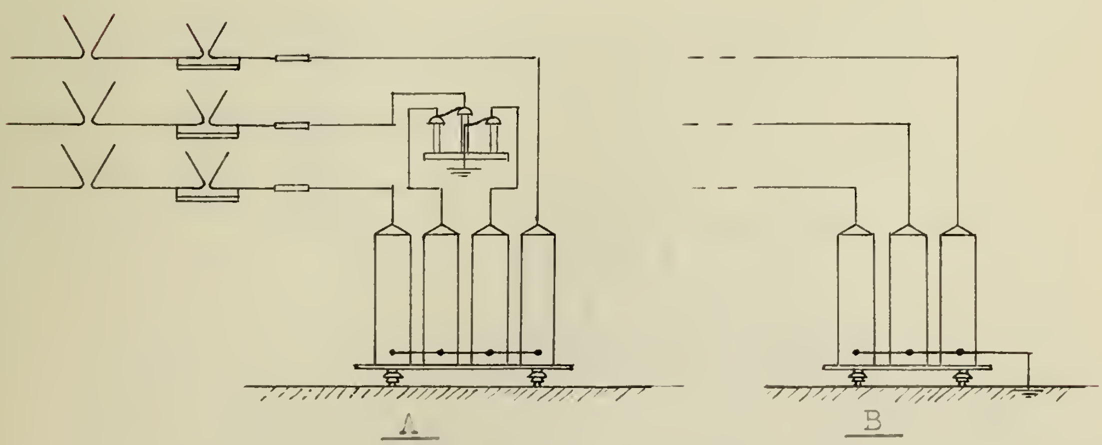

Fig. 120.- Aluminum Arrester Connections.
(11,000 to 13,200 volts.)

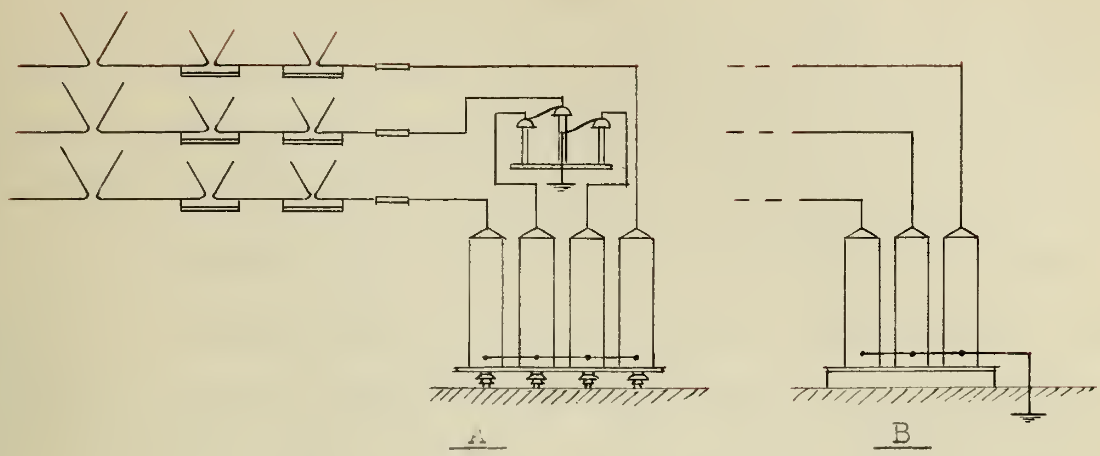

Fig. 121.- Aluminum Arrester Connections.
(11,000 to 110,000 volts.)

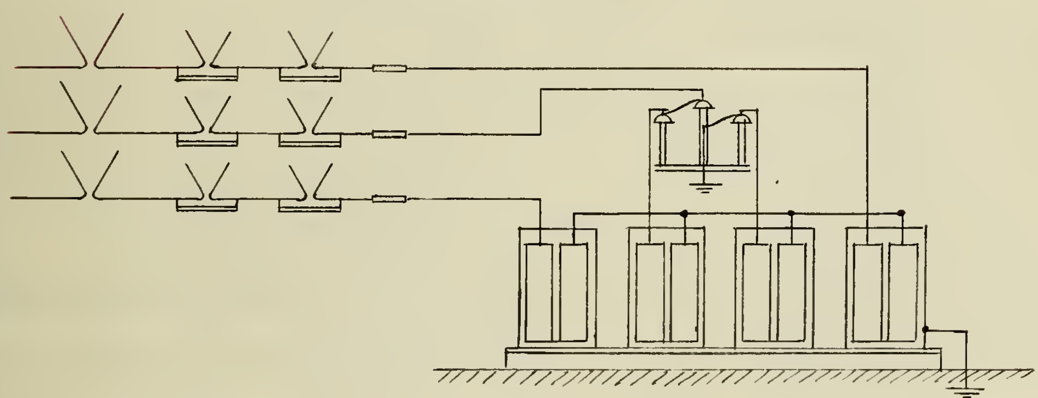

Fig. 122-A. -Aluminum Arrester Connections.
(110,000 volts and Up.)

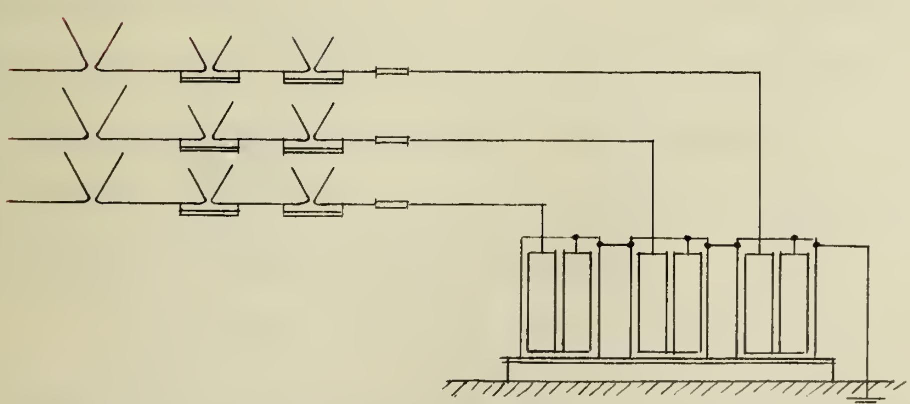

Fig. 122-B.- Aluminum Arrester Connections.
(110,000 volts and Up.)

and substations is now universal. Different shapes of coils are used but the reactive effects are similar. When a traveling wave reaches a choke coil a partial reflection occurs, nearly doubling the potential at the point of reflection. Evidently, the arresters should be connected at this point.

Disturbances in transmissionlines may occur either from line to line or from line to ground. Line-to-line disturbances should preferably be discharged through a path not including the earth. In three phase systems having ungrounded neutrals, line-to-line disturbances can be discharged without interference with the earth; but for grounded neutral systems line-to-line disturbances are discharged through the earth without affecting in any way the equilibrium of the system.

The aluminum cell lightning arrester is continually gaining reputation on account of its good characteristics and it should be recommended where a high degree of protection is desirable.

Figs. 118-A, 119-A, 120-A, 121-A and 122-A represent standard connections and types of aluminum arresters used for different alternating current voltages for three-phase, ungrounded neutral systems. The diagrams B of the same figures represent standard connections for grounded neutral systems of corresponding voltages.

Multigap arresters were generally used until the avent of the aluminum cell arrester. They have been adapted to systems operating up to 60,000 volts. The connections of this type of arrester are very similar to those of the

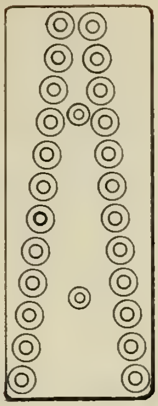

Fig. 123.- Form "V" Multigap Arrester Unit.

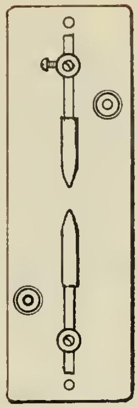

Fig. 124- Adjustable Spark-Gap

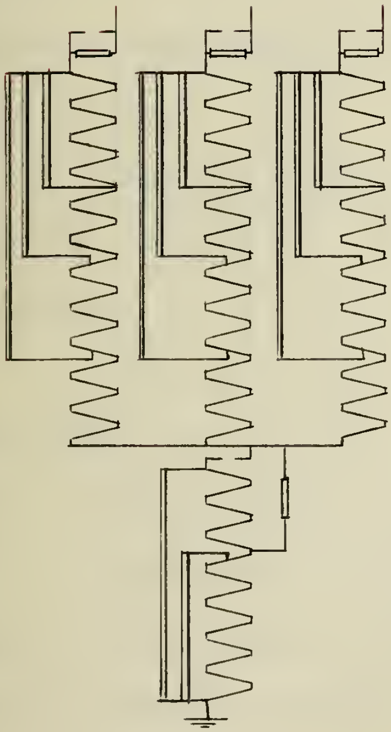

Fig. 125.- Multigap Arrester for Delta or Ungrounded Star Circuits. (35,000 volts)

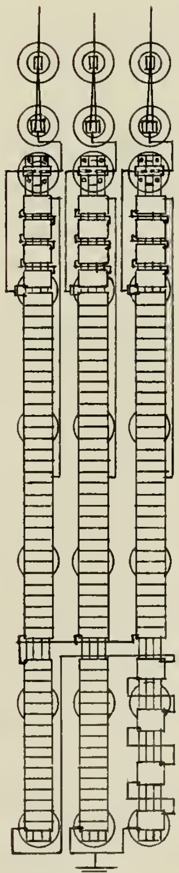

Fig. 126.- Multigap Arrester for Delta or Ungrounded Star Circuits. (60,000 volts)

aluminum cell.

Fig. 123 shows the form "V" gap unit used in building long series of gaps as required for high voltage circuits. An auxiliary spark gap (Fig. 124) is also used under those conditions. This gap is connected between the line and the arrester.

When a multigap arrester is directly connected to a high voltage line, the charging current of the cylinders causes the formation of minute sparks between the cylinders nearest the line. This phenomenon tends to decrease the effectiveness of the arrester but the additional long gap obviates such a trouble to some extent. For lower voltages, (under 35,000 volts), the additional gap is generally shunted with a fuse.

Fig. 125 shows a diagrammatic arrangement of non-arcing gaps for 35,000-volt delta or ungrounded star connected circuits.

Fig. 126 shows a multigap, multiplex alternating current lightning arrester with single blade switches for 60,000 volt, 3 phase, delta or ungrounded star connected circuits.

The object of the multiplex connection of the single legs of the arrester is to admit discharges between lines without passing through the earth, and also discharges between line and ground.

In regard to the installation of multigap arresters a few points must be kept in mind. For 5,000 volts or more, as much space as possible should be provided on the wall and in

front of the arresters for their inspection and for the safe operation of the disconnecting switches. Very often, specially constructed high compartments or separate towers are provided for safe and efficient mounting of these high tension apparatus. The following table gives the proper spacing between multigap arresters as recommended by The General Electric Co.

TABLE II

Voltage	Distance in inches between live parts of adjacent phases	Minimum distance between centers (See note.)
6,000	8 inches	28 inches
10,000	8 "	28 "
12,000	8 "	33 "
15,000	10 "	35 "
20,000	12 "	37 "
25,000	18 "	48 "
30,000	22 "	52 "
35,000	26 "	56 "
40,000	28 "	62 "
45,000	32 "	67 "
50,000	36 "	72 "
60,000	40 "	78 "

Note: If barriers are used, the width of the barrier should be added to the distance given.

The place where arresters are mounted should be dry and warm and before mounting, all wooden parts and insulators should be thoroughly dried.

The Westinghouse Company produces the low-equivalent alternating current lightning arrester described in Chapter V and recommends a different type of connections.

Fig. 127 is a wiring diagram of low equivalent arresters as applied to a three phase, grounded neutral circuit. The

arrester units used in this case are those shown in Fig. 21, Chapter V. These units are mounted on marble slabs.

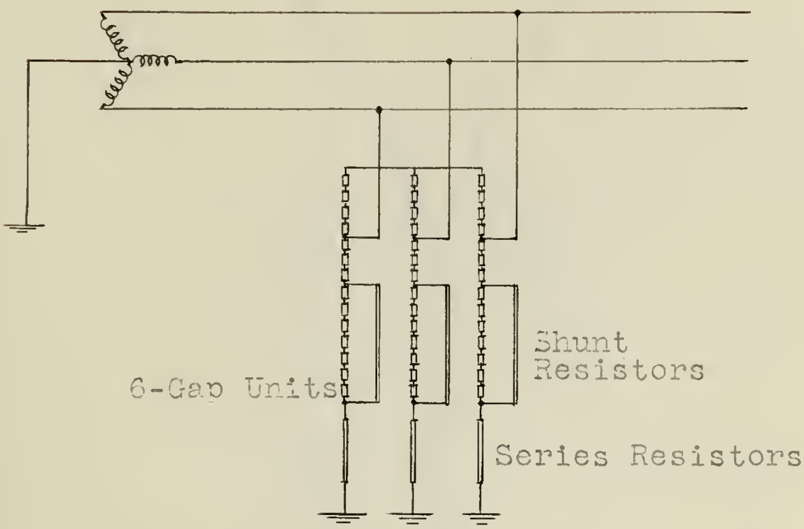

Fig. 127.- Connection of Low-Equivalent Lightning Arresters to an 18,000-volt, Three-Phase, Star Connected Circuit with Grounded Neutral.

The space between active parts of adjacent arresters connected to different sides of the circuit, should not be less, according to R. P. Jackson# than the distance given in the following table.

TABLE III

Voltage		Distance Between Active Parts.
Exceeding	Not Exceeding	
5,700	8,500	6 inches
8,500	12,500	7 "
12,500	18,000	9 "
18,000	25,000	12 "
25,000	29,000	15 "
29,000	37,000	20 "

#--"The Protection of Electric Circuits and Apparatus from Lightning and Similar Disturbances"- Elec. Jour. Apr.,1908.

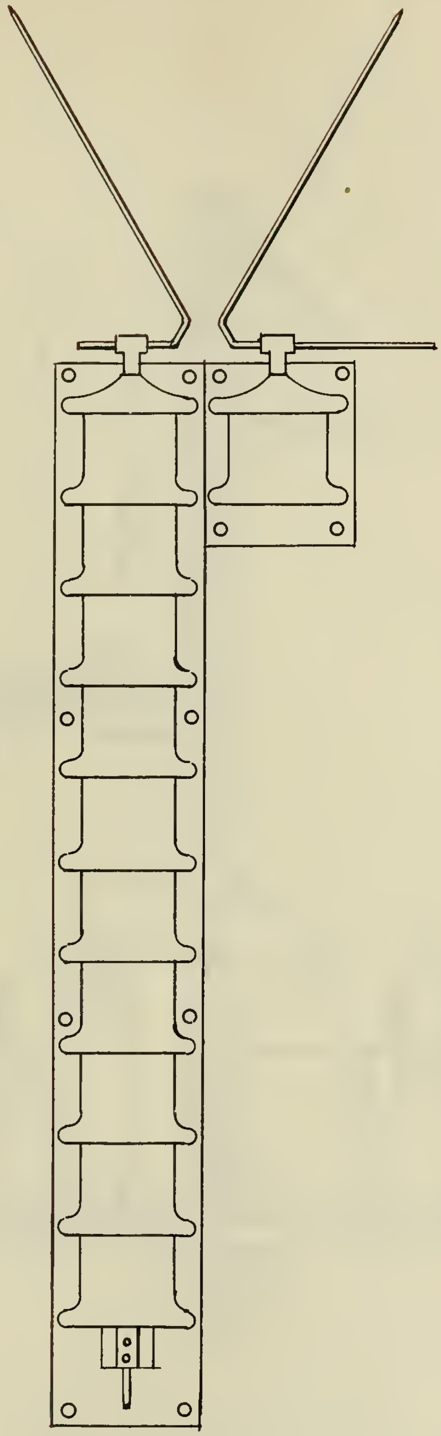

Fig. 128.-- The "Shaw" Lightning Arrester
for High Potential Circuits.

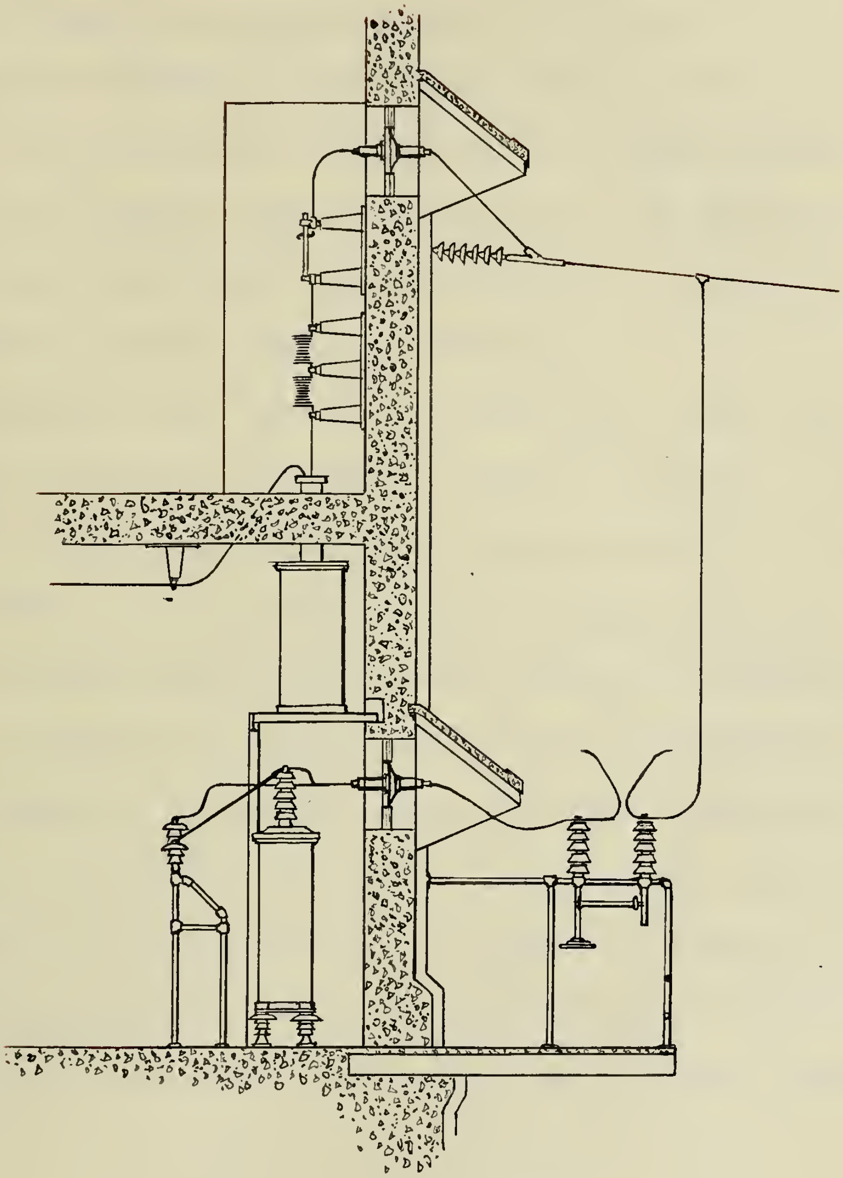

Fig. 129.-- Typical Arrangement of Station Protective Apparatus.

The "Shaw" high resistance carbon lightning arrester, which can be classified under the multigap type, is also used for protection of circuits as high as 100,000 volts. The units are simply the arresters shown in Figs. 40 and 41,(Chapter V) placed in special porcelain housings that can be fitted in rows as shown in Fig. 128. For high voltage protection a horn gap is used in series with the arrester for the same reason that the adjustable gap is used in connection with non-arcing metal multigap arresters.

Whatever type of arresters is used, great care should be taken to insulate the line in passing through the walls or roof of the plant. Under any circumstances, it is advisable to protect such insulators from being covered with sleet or snow that may occasionally cause leakage or discharges to ground. It should be kept in mind, in designing wall or roof outlets, that the action of the choke coils cause the greatest electrical stresses at the end of the line and therefore, a large factor of safety should be allowed in designing the station line outlets. Fig.129 shows a typical arrangement of the protective circuit for a plant of moderate capacity.

PROTECTION OF POWER APPARATUS

With transformers having a large ratio of transformation and operating on high voltage lines, momentary voltages to ground may occur on the low tension side greatly in excess of the normal potential. These rises of potential are called "static disturbances" and in general are the result of a change of static balance on the high tension side and its connecting circuits. In transformers with high ratio of transformation, these static disturbances on the low tension side may cause serious strains in the insulation. It is more serious in high ratio transformers because their insulation is less able to withstand such strains, the induced static voltage being independent of the ratio of transformation.

A method of relieving these disturbances is to place a discharge gap between some point in the secondary winding and the ground. Any voltage much in excess of the normal maximum will cause a discharge to ground over the adjusted opening of the gap. The low-tension side is thus tied to ground during such a discharge while it is normally ungrounded.

The most commonly employed spark gap connections to banks of transformers are shown in Figs. 130 to 143 inclusive. The low tension windings only are shown, as the connection of the high tension windings is in general immaterial. The spark gaps usually employed for this purpose are those shown in Fig. 22.

It is very desirable to prevent disturbances from

 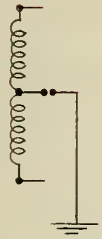 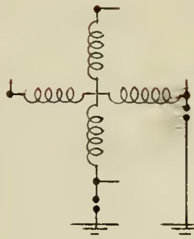 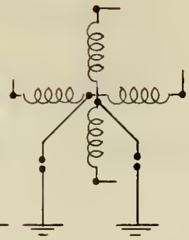 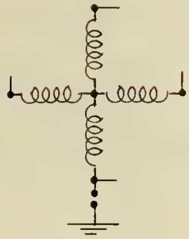 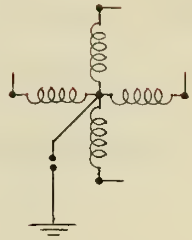

Fig.130. Fig.131. Fig.132. Fig.133. Fig. 134. Fig. 135.

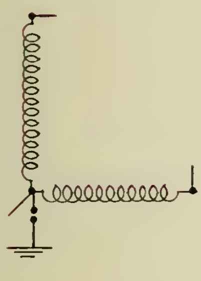 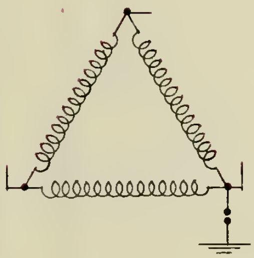 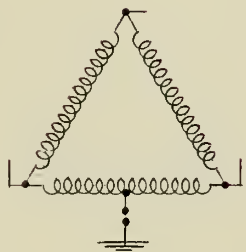 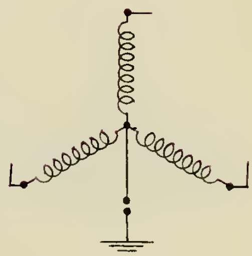

Fig. 136. Fig. 137. Fig. 138. Fig. 139.

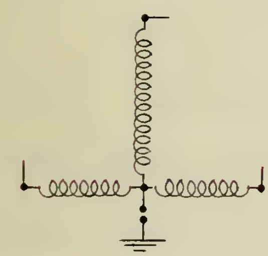 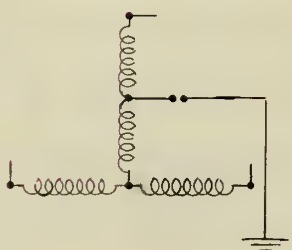 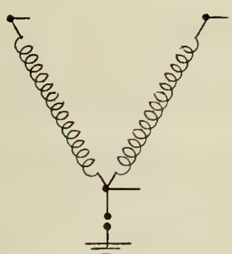 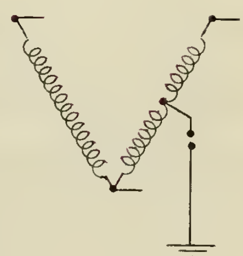

Fig. 140. Fig. 141. Fig. 142. Fig. 143.

entering the high-tension windings of power transformers. L. J. Neall# performed some experiments on the potential stresses to which transformer windings are subjected when a high frequency potential is impressed on them. The object was to determine the effectiveness of choke coils in suppressing high frequency currents.

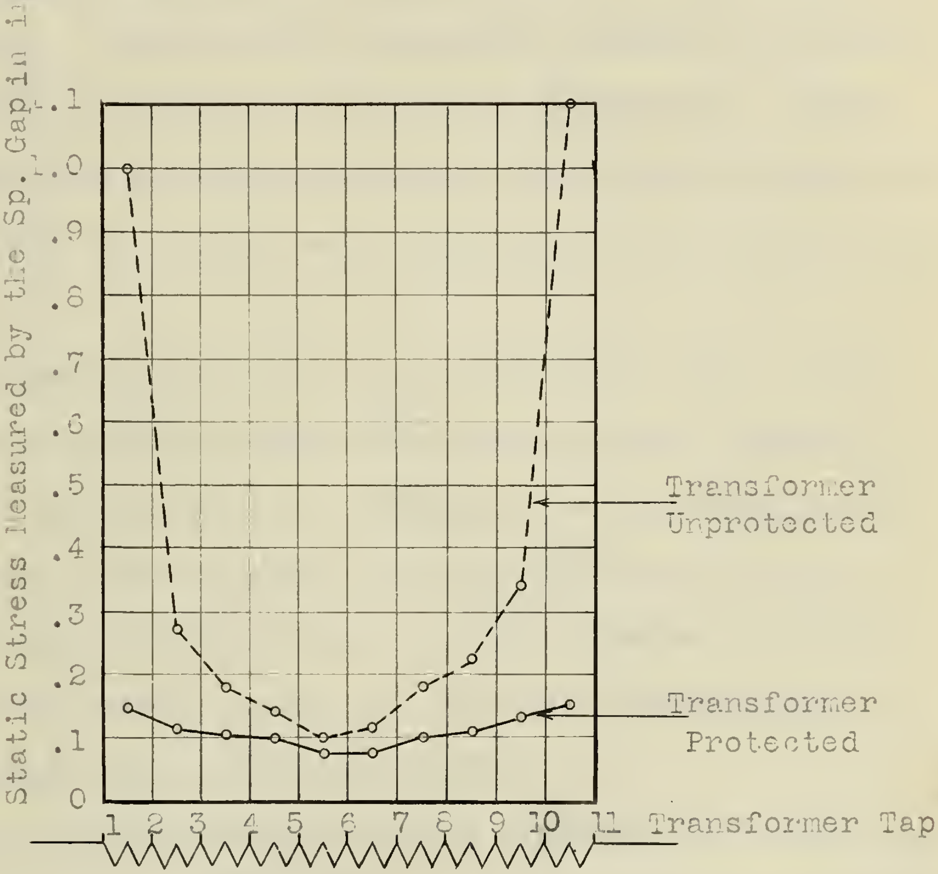

Fig. 144.

Fig. 144 shows graphically the results of the experiments. A number of potential taps were brought out of the transformer and their potential stresses measured by spark gaps. These potential stresses were plotted as shown in the figure.

#--"Protective apparatus" By L. J. Neall. Electric Journal, Oct., 1905.

The relief obtained by the use of choke coils is very clearly brought out. The experiments also confirm the magnitude of the end-turn stresses and the necessity of extra insulation of such turns.

For protection of generators and rotary converters of medium capacity, the condenser type arrester (Fig. 82) is generally used . Elertrolytic arresters, however, offer the maximum protection and are by all means preferable. Where only the generator or rotary converter is to be protected, one set of arresters should be installed between each machine and the bus-bar.

To prevent flashovers on the commutator of a rotary converter arising from sudden overloads or short circuits on the line near the station, the condenser car mounting type arrester may be used and should be connected with the gap short-circuited across the direct current brushes. Electrolytic arresters without series gap also give satisfactory results although they are more expensive.

Where the alternating current side of a converter is supplied through a transformer of high primary voltage, there is a marked tendency to flashover at the converter commutator.

This phenomenon is due to the relative electrical constants of converter and transformer. The transformer represents a condenser of considerable capacity in series with the rotary converter, which is a condenser of less capacity. Such a condition places static strains on the converter insulation in excess of those on the transformer insulation.

The insulation of converters is generally weaker than that of transformers of corresponding capacity, consequently all potential strains will be more intensely felt at the converter. By placing an additional condenser in parallel with the converter, thus increasing its capacity, the potential strain is better distributed so that the highly insulated transformer takes a greater strain. A one microfarad condenser arrester with the spark gap short-circuited will excellently answer the purpose. One condenser should be connected between each lead and the ground on the alternating current side of 600-volt direct current converters and two condensers in case of 1200 or 1500-volt rotaries.

Some protection is afforded by the use of static interrupters but lightning arresters should always be preferred.

Switchboards are so intimately connected with the power apparatus that additonal protection for them is seldom needed. It is, however, advisable to place some verysensitive arresters between the main busses and the ground. Condenser or electrolytic type arresters are occasionally used for this purpose.

CHAPTER VIII

PROTECTION OF ROLLING STOCK EQUIPMENT

Lightning arresters for use on rolling stock equipment should have the following characteristics:

1.-- Portable.

2.-- Rugged mechanically, to provide against continual vibration.

3.-- Small in size.

4.-- Capable of being located in any place or position.

5.-- Should require the minimum inspection and attention.

Where line arresters are not used, the car arresters should be of a high protective ability. Line arresters, where used, need not be as effective as the car arresters, for they are placed at frequent intervals and divide the load correspondingly.

The aluminum arrester has so far given the best satisfaction. This type of arrester is often used with a very small gap in series on account of the continuous leak through the cells. The application of the arrester directly connected is to be recommended wherever lightning is severe and where continuity of sevice is important. A particular example of railway service where the arrester directly connected is advisable without consideration to other factors, is on electric locomotives. The first cost of a locomotive warrants a considerable outlay for any protective device that will give

reasonable protection against damage of the insulation and thus prevent stalling of a train en route.

Putting aside considerations of external lightning, heavy current traction involves great electromagnetic surges and consequent great risks of flashovers on the motor commutators.

The multipath arrester has characteristics very similar to those of the aluminum cell. This type of arrester is particularly fitted for car and line mounting and fulfills nearly all the desirable characteristics of arresters for such a use.

The magnetic blowout arrester is also extensively used for railway service. It has been found necessary to place a resistance in series with this arrester in order to obtain reliable operation of the arc breaking device. The introduction of this resistance limits the discharge through the arrester and consequently its protective value.

The Garton Daniels arresters are adaptable to car and line mounting, but their characteristics make them better adaptable to line service.

The equivalent spark gap of the three latter arresters of similar rating are quoted as follows:

Multipath arrester	0.10 in.
Magnetic Blowout arrester	0.252 "
Garton Daniels arrester	0.213 "

The multipath arrester has over twice as great freedom of discharge than the magnetic blowout or the Garton Daniels type

The condenser type arrester acts almost as a dead short circuit across the apparatus to be protected when high frequency oscillations and surges try to enter it, yet it allows no direct current to flow. This comes quite close to the ideal for a lightning arrester, especially as on railway circuits high frequency troubles are the most serious of all.

For traveling direct current waves, on the other hand, the condenser type arrester is equivalent to many miles of line which the wave has to charge before it can hit the apparatus being protected. This type of arrester is particularly well adapted to car mounting.

The multi-vapo-gap arrester is of such a construction that requires the minimum attention and is therefore adaptable for car as well as for line mounting. Experimental data on the behavior of this arrester at low temperatures will be of great practical interest because the condensation of the water vapor in the discharging chamber may possibly affect the characteristics of the arrester.

Good car protection can also be obtained by the use of the high resistance carbon arresters shown in Figs. 40 and 41 on account of their characteristics and capability of standing the continuous vibration of rolling equipment.

LOCATION OF PROTECTIVE CIRCUITS ON ROLLING EQUIPMENT

A good lightning arrester does not always afford adequate protection to rolling stock equipment. Its location as well as that of the discharging circuit should be carefully determined in order to obtain satisfactory results.

The electromagnetic and electrostatic inductions of the high frequency discharge current may, under certain conditions, cause disturbances in the power and control circuits of cars and locomotives. The nature and magnitude of these phenomena were carefully determined by Creighton, Shavor and Clark#. The experiments were divided into two main sets: First, determination of electromagnetic induction;and second, determination of electrostatic induction.

The first set of experiments consisted essentially of impressing an alternating potential of very high frequency (2,000,000 to 3,000,000 cycles per second) on one of two parallel wires (Fig. 145) and measuring the induced potential on the other by means of the needle gap. First, the bare wire was used varying the distance between wires and then the wires were placed in iron pipes, first the induced wire only, then the inductor wire only and finally both of the wires being inserted.

The following table gives the results of the experi-

#-- "Studies of Protection and Protective Apparatus for Electric Railways". Pro. A. I. E. E., May, 1912.

ments.

TABLE IV.

Electromagnetic Induction between Parallel Wires 6 ft. long.

No Pipe Used		Pipe on Wire 1		Pipe on Wire 2		Pipes on 1 & 2	
Dist. from Cent.	Gap in inches	Dist. from Cent.	Gap in inches	Dist. from Cent.	Gap in inches	Dist. from Cent.	Gap in inches
.4	.35	together	.33	together	.31	together	.27
2	.26	2	.24	2	.25	2	.25
4	.20	4	.19	4	.17	4	.19
6	.16	6	.15	6	.15	6	.14
9	.12	9	.12	9	.13	9	.12
16	.10	16	.09	16	.10	16	.08
22	.09	22	.06	22,	.05	22	.03
30	.05	30	.025	30	.025	30	.015

Note: Gap G was kept 5 inches.

It is seen from this table that inclosing the wires in iron pipes has but little effect on the inductance of the neighboring conductors. To judge from these results, it is obvious that the lightning conductor should be kept as far as possible from any other conductor, especially those of the power circuit.

Fig. 147 show a typical objectionable wiring on a car, Fig. 148 shows a wiring less objectionable but not to be recommended. The most desirable arrangement of arrester and choke coil is that shown in Fig. 149 where the parallel rising wire is carried several feet away from the connection to the arrester. The connections shown in Fig. 150 are not quite as effective as those shown in Fig. 149 due to the greater length of wire in the arrester circuit. If it seems necessary to use the connection of Fig. 150, the arrester should be placed on the roof of the car, in the vestibule or under the car

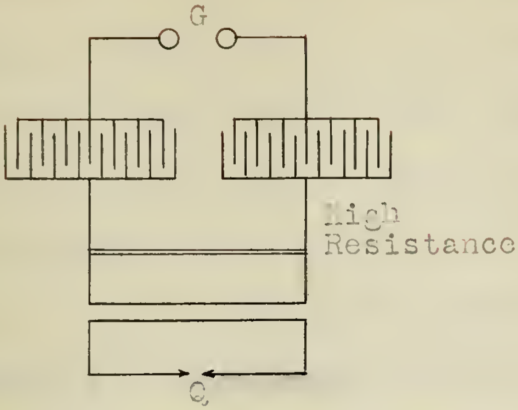

Fig. 145.

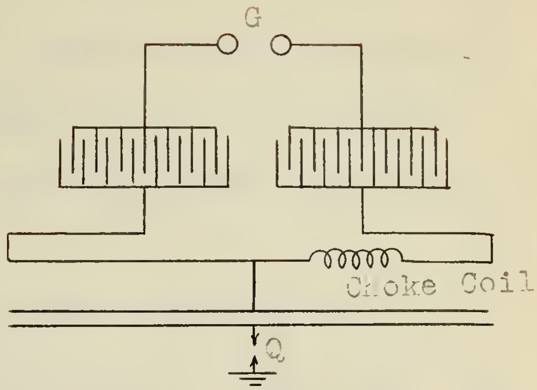

Fig. 146.

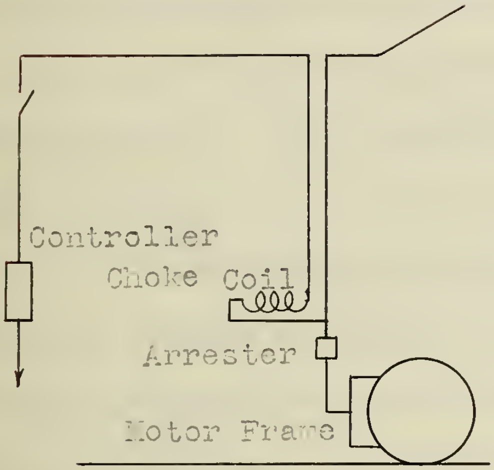

Fig. 147.

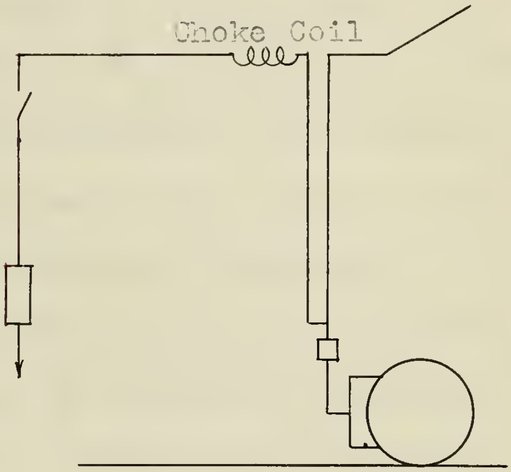

Fig. 148.

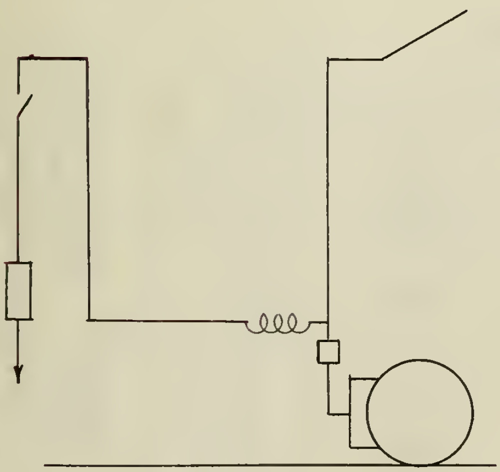

Fig. 149.

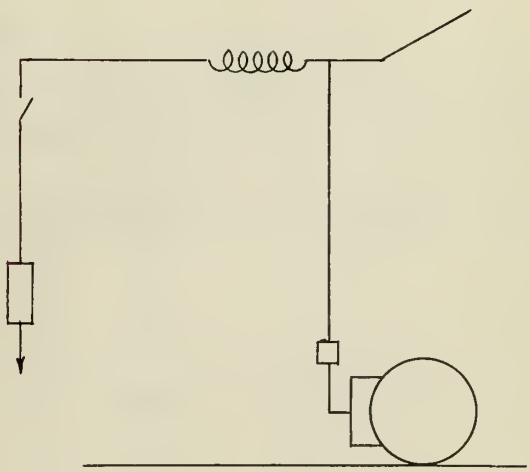

Fig. 150.

without affecting the inductance of the arrester circuit. When such a connection is used, however, the choke coil should be of more ample capacity than that used with the arrangement shown in Fig. 149, in order to offset the greater inductance of the arrester circuit.

The experiments on electrostatic induction were performed with the apparatus arranged as shown in Fig. 146. One of the wires was connected to the static machine and the other to ground through an adjustable gap Q. The voltage impressed on one of the wires was varied by changing the gap G of the static machine. The inductance connected in the primary circuit first consisted of a choke coil having five turns of number 6 wire on a 4-inch core, and later, it was increased to 12 turns. The spark across the gap Q, which represents the insulation of the apparatus on the car, was of sufficient brightness to damage insulation. The following table gives the results of the experiments.

TABLE V.

Electrostatic Induction Between Parallel Wires 30 feet Long.

Gap G in.	Gap Q in.	Spark	Needles	Choke Coil
1	.416	Snappy	Small	5 Turns
1-5/8	.532	"	"	" "
2	.625	Heavy	"	" "
3	.92	"	"	" "
3-1/2	1.19	"	"	" "
3-1/2	1.32	"	Large	12 Turns
3-7/8	1.25	"	"	" "
5	1.30	"	"	" "
3	1.22	"	"	" "
2	1.13	"	"	" "
1-5/8	1.05	Less Bright	"	" "
1	.84	" "	"	" "

If the potential between two parallel wires, as those connected to the choke coil in Fig. 147, reaches a value sufficient to puncture the insulation, then the whole lightning charge goes directly to the apparatus, bypassing all protective devices. Furthermore, such a shunting of the choke coil will not cause burning at the point of discharge, as the dynamic current cannot follow; there will be nothing to indicate to an inspector that the protection of the car has been materially weakened. A simple rule to follow to avoid such a condition is: never bring wires connected to the opposite terminals of the lightning choke coil within about one foot of each other.

Electrostatic induction in car wiring is so easy to avoid that it is only necessary to call attention to the necessity of observing the possibilities of occurrence of the phenomenon.

Every possible precuation should be observed to make the protective circuit on cars and locomotives as effective and simple as possible. Lightning conductors for this use should not be smaller than number 6 copper wire; their joints should always be well soldered; it is preferable not to put lightning conductors through metallic conduits; in case of steel cars, the arrester should be grounded to the steel structure if there is certainty of a perfect connection to the motor frames.

CHAPTER IX

PROTECTION OF COMMUNICATION AND SIGNAL SYSTEMS.

COMMUNICATION SYSTEMS

As a general rule, power transmission systems are paralleled by communication systems owned either by the power company or by some other company. In any case, disturbances caused by the power lines on the communication lines should be avoided as far as practicable.

Fundamentally, the disturbance of a telephone conversation caused by the operation of transmission lines is due to foreign currents being set up in the telephone circuit. In actual practice the disturbing factors come to the telephone lines from the three following causes: first, electromagnetic induction; second, electrostatic induction; and third. leakage.

Let the wire X Y, Fig. 151, represent the disturbing wire and the diagram under it the telephone circuit. If an alternating current is passing through the line conductor, the electromotive force induced in the telephone conductor nearer the line exceeds that induced in the other wire. Consequently, a current is forced on the telephone circuit in the direction of the arrows for an instantaneous current in the line from X to Y. Therefore, an alternating current flows through the telephone apparatus causing disagreable

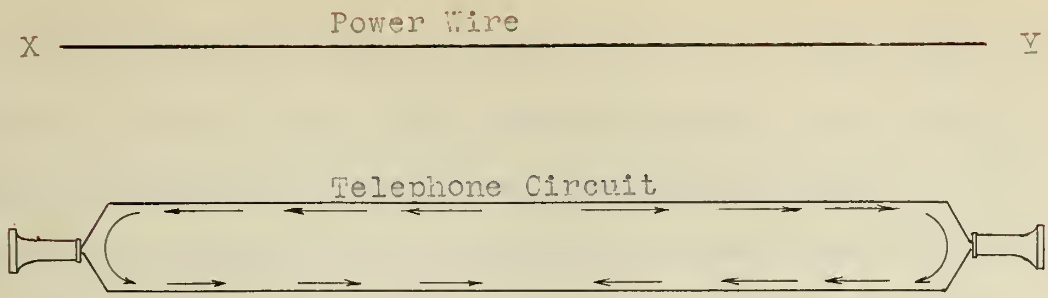

Fig. 151.

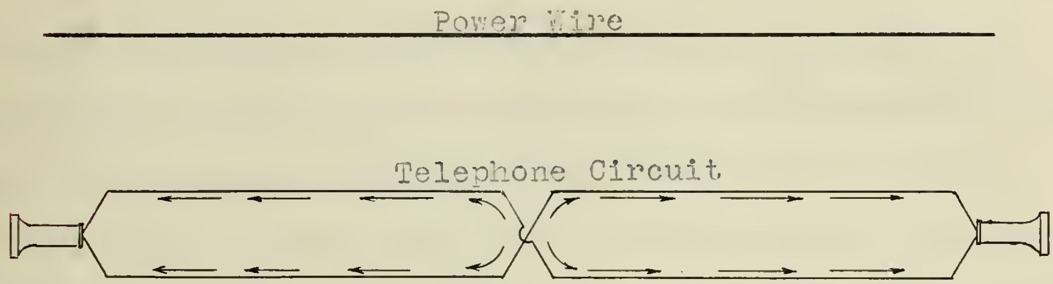

Fig. 152.

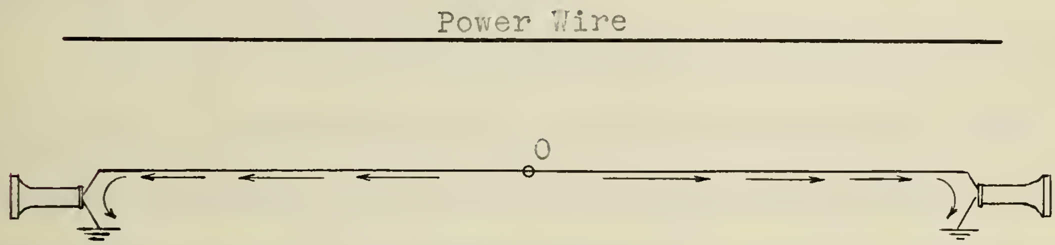

Fig. 153.

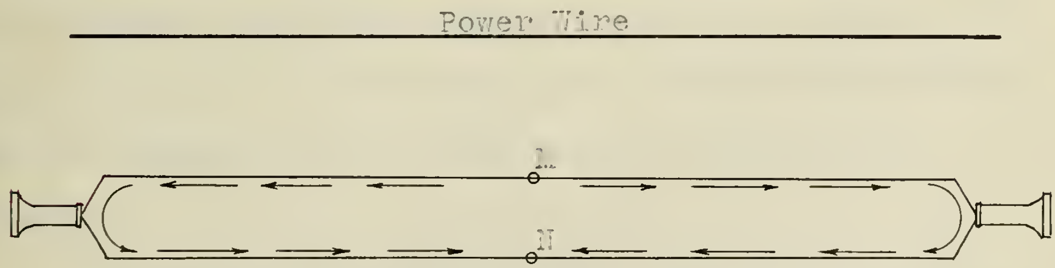

Fig. 154.

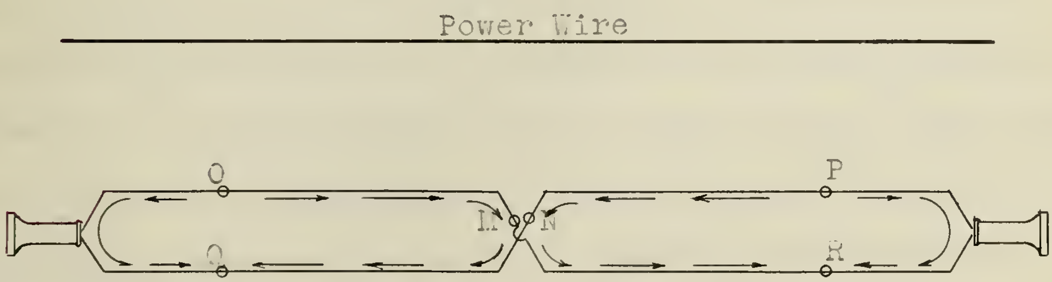

Fig. 155.

noises in the receivers. By transposition of the telephone lines as shown in Fig. 152, equal potentials are induced in both lines and no current flows through the receivers. The number of transpositions necessary to secure this condition is determined from a study of the distributing circuit.

The total amount of electromagnetic disturbance depends upon the following factors: First, intensity of current in the distributing wire; second, distance of the disturbing wire from the telephone circuit; third, the relative distance between the disturbing wires and the two sides of the telephone circuit; and fourth, the distance which the disturbing wire parallels the telephone circuit.

The electrostatic effect of the disturbing line upon a grounded telephone circuit is shown in Fig. 153. When the charge in induced current flows from the middle point 0 towards both grounds. This current would cause a disturbance in the telephone receivers. Point 0 is thus a neutral point since no current flows through it. Points M and N (Fig. 154) are the neutral points in the case of an ungrounded telephone circuit.

It has been shown that the remedy for electromagnetic induction is to transpose the circuit at the electrical centers of the exposures. In case of an ordinary uniform exposure, one transposition in the center of the same will be sufficient to eliminate the effects of electromagnetic induction. But such is not the case with the effects of electrostatic induction. Referring to Fig. 155 , which repre-

sents a line, with one transposition, under electrostatic induction, the points O, P, Q and R represent the neutral points. The center points M and N are no longer neutral. Only a small portion of the total charge now passes through the receivers. Therefore, if the number of transpositions be multiplied greatly, it is evident that the telephone circuit may be broken into so many small portions that the charge upon each one of these will be so minute that the disturbances in the receiver will become imperceptible.

The third factor to be considered, which has been referred to as leakage, is a disturbance due to some of the following causes: passage of current from the transmission line itself through limbs of trees, bad insulation on either telephone or transmission line when on the same pole lines and also by poor insulation of the telephone line, permitting currents to escape to earth disturbing the balance of potential gained by proper transposition. These disturbances can be eliminated by properly insulating both power and communication systems.

Another source of disturbance of widespread interest to rural communities adjacent to interurban or electrified lines is the electrification of the ground in the vecinity of the rails. The concentration of heavy loads on electric railway lines causes considerable difference of potential between distant points in the rail and consequently in the neighboring soil. Telephones grounded to soils subjected to considerable difference of potential act as a shunt to the

rail line when put in communication. Many experiments in connection with this type of disturbances have demonstrated that there are only two practical remedies, one of which is to make a metallic circuit of the line, and the other is to remove the ground from any telephone affected to a point outside of the disturbed zone.

The subject of inductive interference was carefully investigated by a Joint Committee on Inductive Interference appointed by the California Railroad Commission. The results of the investigation are briefly summarized as follows:#

1.-- Interference to telephone circuits, under normal operating conditions of power circuits, arises almost wholly from harmonic voltages and currents. This is due chiefly to the fact that the frequencies of the harmonics generally present in the voltage and current waves cover a considerable portion of the range of voice frequencies and particularly those at which telephone instruments and the human ear are of maximum sensitibility.

2.-- The effect of induction, at the fundamental frequency, on telephone circuits is comparatively unimportant unless it is of a magnitude sufficient to constitute a physical hazard. This is due to the fact that the fundamental approaches the lower limit of audible frequencies at which the telephone and human ear are not sufficiently responsive.

3.-- Interference to telegraph and other signaling

#-- Report of Joint Committee on Inductive Interference, Telephony, Sept. 19, 1914.

circuits is due principally to the fundamental and lower harmonics.

4.-- The power circuit currents and voltages may be divided into two factors: balanced and residual. Balanced currents or voltages are those whose instantaneous values add vectorially to zero, but when such addition results in a definite vector this constitutes the residual voltage or current, as the case may be. Residual currents and voltages act inductively in a similar manner to single phase currents and voltages acting in a circuit composed of the line conductors in parallel, with earth return, which is a condition favorable to very large induction. Moreover, such a circuit, including the earth as one side, cannot be transposed. Transpositions in the power circuit cannot reduce the inductive effect of the residuals, except as they reduce the magnitude of the residuals themselves. The inductive interference arising from such currents and voltages can be reduced, in the case of metallic circuits such as telephone circuits, only by transposition.

5.-- Inductive interference to communication systems, arising from unbalanced voltages and currents, can in a large measure be prevented by an adequate system of transpositions applied to both power and communication systems (assuming the latter are metallic), and located with regard to each other.

6.-- Abnormal conditions and at times switching operations produce transient disturbances of a very severe character. This is due to the fact that abnormal conditions almost

invariably give rise to residuals of large magnitude often including high harmonics.

The following is an abstract of the rules proposed by the Committee:

1.-- Every reasonable effort shall be made to avoid new parallelism. In case it is impracticable to secure adequate separation between power and communication lines parallelism will be permitted subject to the conditions set forth in 2.

2.--(a)-The minimum horizontal separation between power and communication lines shall be equal to the height of the taller line.

(b)-The power company shall excercise due diligence to keep its lines as closely balanced as practicable.

(c)-Residual currents and voltages must be kept as low as practicable.

(d)-An adequate system of transpositions shall be installed in the power and communication circuits, provided the latter is metallic. Transpositions in either circuit shall be made with regard to the other.

(e)-Each new power circuit isolated from the ground shall be transposed throughout its entire length in such a manner as to balance the electrostatic capacity to earth of each one of its conductors so as to avoid inequalities of their voltages to earth, which would create inductive interference.

(f)-To facilitate the application of effective

transpositions, both parties shall endeavor to maintain uniform separation and uniform arrangement of conductors.

(g)--1-On any power circuit involved in a parallel, no grounded single phase or grounded open-star transformer connections shall be employed. (This does not apply to railroads operating alternating current trolleys with ground return, which are covered by section 5.)

2-On a power circuit involved in a parallel, no star-connected transformers with grounded neutral shall be employed unless delta-connected secondary or tertiary or other equivalent means are used for suppressing the third harmonic components of the residual currents and voltages originated at the transformers.

3-Where single phase loads are connected to a polyphase power circuit involved in a parallel, the power company shall endeavor to arrange successive connections of this type so as to equalize loads upon the several phases.

4-On a three phase circuit involved in a parallel, the power company shall use, wherever practicable, a closed-delta in preference to an open-delta connection and where the latter is employed, an effort shall be made to distribute such connections upon the several phases.

(h)--A power circuit involved in a parallel shall be equipped, between the source of supply and the parallel, with oil switches interconnected for simultaneous operation.

(i)--All switching on a system involved in a parallel shall be done by means of oil switches.

(j)-The use of air switches in a power circuit involved in a parallel is prohibited except for purposes of isolating sections of dead line or for disconnecting transformers under no load.

(k)-A power circuit involved in a parallel shall not be operated at any time with an open-grounded or short-circuited line wire or wires or transformer winding.

(l)-If the power circuit is isolated from ground, indicating devices shall be installed at the power house to inform the operator immediately of abnormal conditions.

(m)-In case of the opening of an oil switch due to an abnormal condition, such switch may be closed once. If opened a second time owing to the continuance of the fault or abnormal condition, said switch shall not be closed again until the line has been sectionalized and the trouble isolated and corrected.

(n)-Wherever a neutral ground connection is employed on a circuit involved in a parallel, an ammeter shall be installed on all neutral connections at the main generating station and substations of the power system.

(o)-Where a power system is equipped with electrolytic lightning arresters so charged as to cause inductive interference in communication circuits, the method of charging the arresters shall be modified to eliminate disturbances as far as possible. The charging of such lightning arresters shall be done at such a time as to give a minimum liability of interference with the communication system operation.

preferably between the hours of 2 and 4 a. m.

(p)-The power company shall make every effort to obtain generators and synchronous motors giving as nearly as possible pure sine waves of voltage at normal frequency.

(q)-In order that the wave shapes of voltage and current may be distorted as little as practicable by transformers, the main line transformers employed shall have an exciting current as low as consistent with good practice.

3.--The following sections of 2 shall apply also to power circuits involved in existing parallels: b, i, j, k, l, n, o, p, q, g-3 and g-4.

4.--At the option of the company operating the communication circuit or circuits, any of the provisions 2 and 3 may be waived provided that such waiver does not increase the hazard.

5.--It is recognized that railroads operating alternating current trolleys, with ground return, create serious inductive interference with parallel communication circuits. In the present state of the art, no means of completely overcoming inductive interference from such parallels is known, hence they are to be avoided if possible and where unavoidable, the responsibilities arising therefrom must be settled by mutual agreement.

These rules apply generally to communication systems not owned by the power company, but in any case they should be applied wherever serious inductive interference occurs.

The importance of a reliable communication system is

oftentimes overlooked by the power companies. They disregard the fact that such systems are of paramount importance especially in the case of trouble. Unfortunately, under such conditions, the communication system, if not properly installed and protected, is not only absolutely worthless but a serious source of danger to the operators.

The proper installation of communication lines has been previously discussed but nothing has been said about proper protection against internal and external lightning disturbances to which they are occasionally subjected.

As a general rule, power companies have private telephone service which is installed and protected to accommodate their particular conditions.

There are two ways of installing telephone circuits for the exclusive use of power companies: First, line installed on separate poles; and second, line installed on the power line poles or towers.

In the first case, the telephone line is more susceptible to external lightning disturbances than to those produced by internal lightning; and in the second case, the reverse is true. If a line is strung on separate poles, there is nothing to protect it from atmospheric disturbances except the ground wires strung along occasional poles. Ordinarily, every fifth pole is fitted with a ground wire that projects a few inches from the top of the pole. A line of this kind is hardly affected by the induction of disturbances on the power circuit, on account of the distance from it.

When the telephone line is supported by the power line poles, the distance from the power wires is relatively small and induced disturbances are correspondingly large.

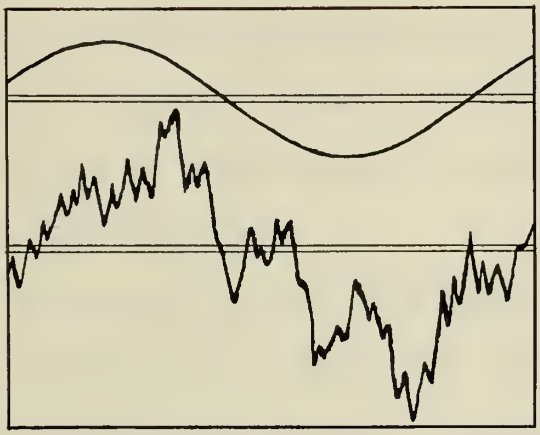

Fig. 156.-Induced Current in a Telephone Line 10 feet under a 33,000-volt Power Line.#

Fig. 156 is an oscillogram obtained by E. E. F. Creighton showing the magnitude of the induced current in a telephone line 10 feet from the power wires.

Atmospheric disturbances, however, seldom affect the telephone line directly due to the protection of the power circuit ground wire. But the indirect disturbances are also of a serious character.

What was said about transposition of telephone wires

#--"Oscillographic Studies Related to Protective Apparatus". By E. E. F. Creighton, Gen. Elec. Rev., June, 1913.

should be emphasised in cases like this, where the telephone line is in such proximity to the power circuit. Besides this transposition, lightning protective apparatus of special characteristics should be connected to the line to relieve it from abnormal potential stresses and save the telephone apparatus.

In order to prevent traveling disturbances from reaching the apparatus, telephone transformers are used. They are an insulation barrier of 25,000-volt test between the telephone instruments and the lines.

Induced potentials on the telephone lines can be reduced by transposition of the wires and by the use of drainage coils. The high-tension coils of a 2,200-volt distributing transformer may effectively be used for this purpose. The high tesion windings of the transformer should be connected in series with the middle point grounded and the secondaries open. The coils should be connected across the line through suitable cut-outs.

The size of the transformer to be used as a drainage coil depends on the following factors:

1.-- Voltage of the power circuit.

2.-- Distance of telephone lines from power circuit.

3.-- Number of transformers used.

4.-- Increase of induced potential due to accidental conditions on the power circuit, such as arcing grounds, open-circuiting of one line, short circuits, etc.

The higher the power voltage and the nearer to the

power circuit the telephone wires are located, the larger the transformer required. The number of transformers used has been generally settled by experience at two or three for the average system. The fourth factor is problematical as it depends upon operating and local conditions. The size of transformer selected should allow a factor of safety of at least five times the normal conditions so as to insure contunuity of service.

Additional protection should be provided near the telephone in order to discharge the line of abnormal potentials to ground and between lines. Spark gaps are generally used for this purpose. The vacuum tube lightning arrester described in Chapter V has all the desirable characteristics for such use. Fig. 23 represents a combination of arresters particularly suited for telephone protection. The sesitivity of the vacuum arrester and the discharging capacity of the non-arcing gaps are simply combined in this arrangement.

As the position of the telphone circuit with respect to the transmission circuit determines the likelihood of troubles due to crosses or induction, the telephone circuits have been classified with this point in view:#

Class 1.-- Telephone circuits which do not cross or parallel power lines.

Class 2.-- Telephone circuits which cross but do not parallel power lines.

#--"Protection of Telephone Circuits Used in Electric Power Distribution." By E. M. Shelton, Gen. Elec. Rev., 12-1916.

Class 3.-- Telephone circuits which parallel power lines but are not on the same towers or poles and do not cross power lines.

Class 4.-- Telephone circuits which are on the towers or poles of the power lines.

Specific recommendations for the protection of the telephone circuit, according to the classification of the circuit into which it falls, are as follows:

Class 1.-- Disturbances: Lightning.

Recommendations: Vacuum tube lightning arresters from each line to ground at all telephone stations.

Class 2.-- Disturbances: These circuits are subject to lightning disturbances and to contact with the high voltage power lines through broken wires, etc.

Recommendations: Combined double pole fuse switch and lightning arrester in series with the main telephone line on both sides of crossing at nearest telephone stations, and lightning arresters as shown in Fig. 157 at all other stations.

Class 3.-- Disturbances: These circuits are subject to lightning disturbances and electromagnetic and electrostatic inductions. They are not subject to contact with power lines.

Recommendations: 1.-Insulating transformers at telephone stations.

2.-Combined double pole fuse switch and lightning arrester at all telephone stations on the line side

of the insulating transformer.

3.-Drainage coils, preferably at each end of the line.

Diagram of connections: A diagram of connections for the apparatus used for this class of telephone circuits is shown in Fig. 157. The double pole horn gap shown on the diagram is not used for this class of circuit but on circuits coming under class 4.

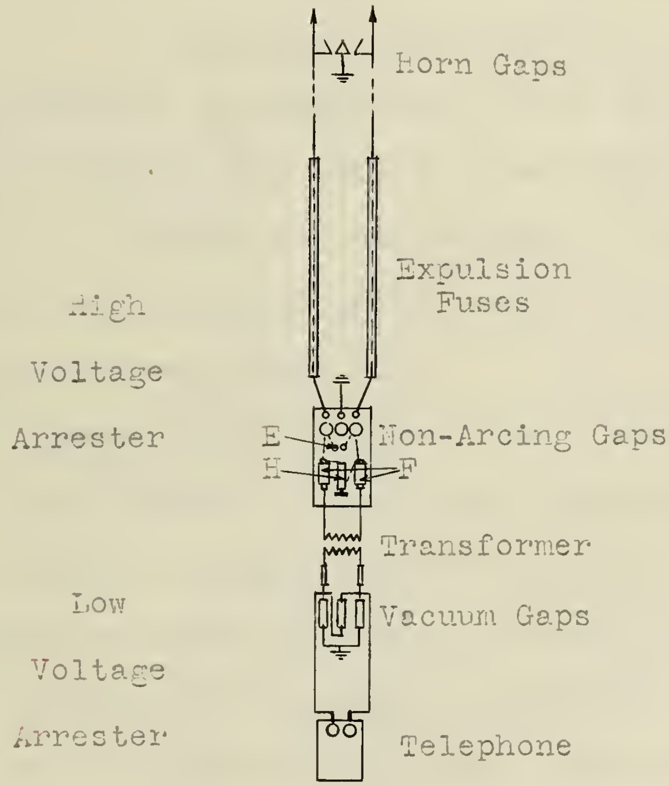

Fig. 157.-Telephone Protective Circuit.

Class 4.--Disturbances: These circuits are subject to lightning disturbances, electrostatic and electromagnetic inductions and to crosses with power lines.

Recommendations: 1.-Insulating transformers at all telephone stations.

2.-Combined double pole fuse switch and lightning arrester at all telephone stations on the line side of the insulating transformer.

3.-Double pole horn gap across line at each station on the line side of all other apparatus, for the protection of insulators on telephone circuit in case of crosses with the power lines after series fuses are blown.

4.-Drainage coils installed at each end of the line; possibly, an additional coil at the middle, if the voltage to ground is not held to a safe value by two coils.

Diagram of connections: A diagram of connections for the apparatus used on this class of telephone circuits is shown in Fig. 157.

This arrester consists of two parts insulated from each other by the telephone transformer: the high voltage arrester and the low voltage arrester as noted in the figure. The high voltage arrester consists of a double horn gap to ground which operates only in cases of emergency, after the expulsion fuses are blown off; the fuses lead to a double non-arcing metal gap to ground which is shunted by a very small gap E and by the vacuum gap H. One side of the telephone transformer is connected to the gaps through the choke coils F. The other side of the transformer connects, through suitable fuses, to a combination of vacuum gaps which protect the telephone terminals from line-to-line and line-to-ground

disturbances.

The high voltage arrester alone affords considerable protection for ordinary cases and the double horn gap is used only in cases where there is danger of a cross with a high voltage power line.

SIGNAL SYSTEMS

Modern systems of railway signaling in this country operate on the well known automatic and interlocking principle. They can be classified into three types: the mechanical, the electro-pneumatic and the all electric.

The successful operation of the second and third classes of signal systems depends largely on the proper protection for the electrical equipment against lightning disturbances.

In studying the protection of these systems, there are three main factors to be considered: first, the nature of the circuit and the importance of the service; second, the disturbances that are to be experienced; and third, the nature and type of apparatus connected to the circuit.

For adequate protection against lightning, a discharge path having a low spark potential is necessary; at the same time the path must be such that will not permanently ground or short-circuit the system. The vacuum tube lightning arrester described in Chapter V admirably fulfills both requirements. This type of arrester should be installed mainly near the terminals of the apparatus. A good ground connection is necessary for each station.

Transformers should always be protected by fuses of ample capacity in order to insure continuity of service.

The charging system should be protected at all stations with magnetic blowout arresters. Aluminum arresters are not

very well adapted for this particular use, except at stations where they can be properly attended.

In alternating current systems, the feeders should be protected by electrolytic arresters and choke coils.

The step-down transformers should be protected with graded shunt resistance multigap arresters or compression chamber arresters in combination with choke coils.

If stations are long distances apart, line arresters should be used at frequent intervals.

C H A P T E R X

PROTECTION OF BUILDINGS AND STRUCTURES

Proper lightning protection for buildings and structures is the oldest question in its field but is still being investigated. The value of this type of lightning protection is still questioned by some engineers. Many investigations have been carried on to determine the effectiveness of building protection. In 1914 some insurance companies undertook an investigation of the usefulness of lightning rods on houses, arriving at the conclusion that in Ontario, Canada, out of 7,000 unprotected buildings, 37 were struck during a certain period of time and out of 7,000 protected ones, only 2 were struck during the same period. Therefore 35 buildings were saved out of 37 expected to be struck; or a probable protection of 94.5% was obtained with uninspected rod construction.#

The reports of some insurance companies in Michigan show that a company insuring rodded and inspected buildings paid $32.00 claims during 4 years on $55,172,075 risk, and another company insuring both rodded and unprotected buildings paid $32,269 claims during the same period, having a total risk of $59,567,272. The loss was practically all on unprotected buildings aggregating $47,753,818 in value risks. Comparing the reports of the two companies, it is clear that,

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#--"Ben. Franklin Vindicated" Eng. News, Oct. 8, 1914.

for each dollar damage on protected buildings there was paid $1,168 on unprotected ones; an obvious protection of 99.9 per cent.

Judging from these results, lightning protection is of considerable practical value and should be given corresponding attention.

Experience seems to have settled beyond reasonable doubt that, if properly installed, lightning rods afford considerable protection. Any lightning rod "draws lightning" if by the expression is meant that under certain conditions, it prepares an easier path for the lightning discharge than would be the case without it. The conducting streamers issuing from the rod tend to equalize the potential between earth and cloud, thus diminishing the severity of the stroke and possibly preventing it altogether. Yet it may also be argued that unless there are many such streamers, the rod cannot always cope with the situation and a stroke may result from them.

An ordinary building cannot have absolute protection against lightning. Lightning rods unquestionably afford some protection but in many cases, may make matters worse. Assume for instance that a large building is equipped with a high but broken rod or a rod having poor joints or high resistance to ground. Such a rod could serve the function of equalizing the potential between cloud and earth almost as effectively as a good rod, and were there a sufficient number, it is conceivable that the neutralization of potential

would be so complete as to make a flash discharge practically impossible. However, a building having one rod only is considered at present. The rod is assumed to be projecting considerably above the building. If the electric tension is great, streamers are emitted from the conductor points, ionizing the air and inviting the discharge. The question is then: How can such a rod take care of a discharge? In the average case of a poor conductor, the voltage drop is so great that it is far easier for the current to split up in a number of paths and enter the building than to confine itself to the rod. Consequently, a defective protective system on a building may expose it to electric discharges which it cannot take care of.

The number of rods that should be installed on a building depends directly on the size of the building and its cost, and in case of a manufacturing establishment, on the nature of its contents. In the average case it is customary to install a lightning rod for each 500 to 1000 square feet of building ground area. In the case of very expensive buildings the area per lightning rod should be correspondingly reduced. Buildings where explosive materials are manufactured or stored should have a large number of lightning rods, to correspond with the danger of igniting the contents.

Lightning rods should be properly located in any case. They should always be placed outside of the building and it is advisable to have the conductors at a reasonable distance form the walls of the building. The rods should be kept at

at considerable distances from gas pipes, water pipes and balconies or places where persons might be during the storm.

The materials that should be used for ground conductors were discussed in Chapters III and IV. It should be added, however, that in cities, on account of the fuel gases, soot and other polluting substances in the air, copper conductors should be used in preference to galvanized iron or steel, on account of the rapid deterioration of the latter under such conditions. This deterioration is due to the formation of certain acids by the combination of some constituents of fuel gases with water. These acids attack iron and zinc more readily than they do copper. Galvanized iron ground conductors for building protection are recommended where such restrictions do not exist.

Expensive sharp points offer little advantage over ordinary rather blunt points. The rods may advantageously terminate in a number of points projecting only a short distance above the part to be protected.

Smoke stacks should have at least one air terminal projecting a few feet above the top. The strands of the conductor can be spread to form a trident but it is better to employ a solid copper point with three bars firmly fixed. In these cases copper conductors should always be used on account of the action of fuel gases. Both horizontal and vertical conductors should be kept a few inches from the structure.

Steel framed buildings are rarely damaged by lightning.

This is due perhaps to the large electrostatic capacity of the structure and to its ample connection to ground. Nevertheless, such buildings should be furnished with the usual number of air terminals.

All metallic towers and special structures for outdoor substations or for any other purpose should be thoroughly grounded by means of plate or pipe grounding devices.

CHAPTER XI

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